Frontpiece: Looking Southwest from the Deans towards Mount Grey.

"We learn geology the morning after the
earthquake."
- Ralph Waldo Emerson

ACTIVE TECTONICS, GEOMORPHOLOGY AND GROUNDWATER RECHARGE TO THE WAIPARA – KOWAI ZONE, NORTH CANTERBURY

A thesis submitted in partial fulfilment of the requirements for the Degree

of Master of Science in Engineering Geology

in the University of Canterbury

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Abstract

The Waipara – Kowai groundwater allocation zones (referred to as zones) are located 50 kilometers North of Christchurch. Land use in the Waipara zone has evolved from dry land farming towards horticultural and irrigated pastoral farming, and as such the demand for groundwater resources has increased significantly. Recent ^{14}C age dating has shown that deep wells tap >1000 years old water, raising concerns about possible resource mining. The Kowai zone has had minimal regional hydrogeological investigations and previously little is known about the groundwater resources here.

The Waipara – Kowai zones are located near obliquely convergent plate margin and the Porters Pass Fault System. Recent (early Quaternary) deformation has been noted by workers along the basin margins and associated with emerging structures within these zones. These emerging faults and folds are thought to be acting as hydrological barriers, hindering the passage of groundwater.

A geomorphic map was constructed for this study based on existing soils maps, limited field soil surveys and morphometric analysis. Nine geomorphic surfaces are described, with inferred ages of modern to >73 ka. The geomorphic investigation revealed that the Kowai zone surface is stepped, with increasing thickness of loess up gradient on the downlands. Near the coast there is intercalated terrestrial and marine sediments, to the West overlying the Kowai Formation are small alluvial fans. In the Waipara zone the Waipara fan dominates the central portion of the basin, with smaller fluvial and alluvial fans building out from the margins.

Groundwater recharge was investigated using chemical, isotopic, water level observations and a simple water balance. It was found that in the Kowai zone the major recharge sources were the rainfall, losses from the rivers and streams. The Southern region of the Waipara zone is recharged by rainfall with small contributions from the Kowai River (North Branch). In the Northern part of the Waipara zone groundwater recharge is derived from rainfall and losses from streams. The groundwater systems are conceptualized as being topographically driven, with slope – basin floors interactions being an important source of groundwater recharge.

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1 Chapter one: Background and objectives

1.1 Study area

The study area is located approximately 50 km North of Christchurch between the Ashley River and approximately the settlement of Spye. The field area encompasses Environment Canterbury's Waipara and Kowai groundwater allocation zones (Figure 1.1). The Waipara groundwater allocation zone is contained within the Waipara alluvial basin (here referred to as simply the Waipara basin).

The Southern boundary is defined by the Ashley River, with the Kowai (North and South branches) located centrally. The Waipara River is the most Northerly significant river in the study area. For convenience the Kowai River branches will be referred to as SB (South branch) and NB (North branch). The Pacific Ocean marks the Southeast boundary with all other boundaries being defined by the peaks of the mountains and hills that ring the basins (See Figure 1.1 for locations and location names). The largest townships in the study area are (from the South) Sefton, Leithfield, Amberley and Waipara.

1.2 Introduction

Land use within Environment Canterbury's Waipara Groundwater allocation zone (referred to hereafter as "zone") has rapidly evolved over the past two decades from predominately dry land pastoral farming towards horticulture and in particular viticulture (per com. J Weeber 2008). As a result there has been a significant increase in demand for the groundwater resource. The Waipara basin is in a tectonically active area and proximity to the coast means that Pleistocene sea-level changes and aggradation events interact with tectonics and together these factors control the geometry and distribution of sediments within the basin.

The Southern Kowai zone on the coastal slopes has had minimal region wide hydrogeological investigations. In itself this represents a gap in the knowledge of the Canterbury groundwater systems. It is also likely that there are structures (folds and faults) within this zone that have yet to be recognised. The Kowai zone has had minimal investigations into geomorphic and active tectonic processes related to the creation and subsequent alteration of the groundwater system.

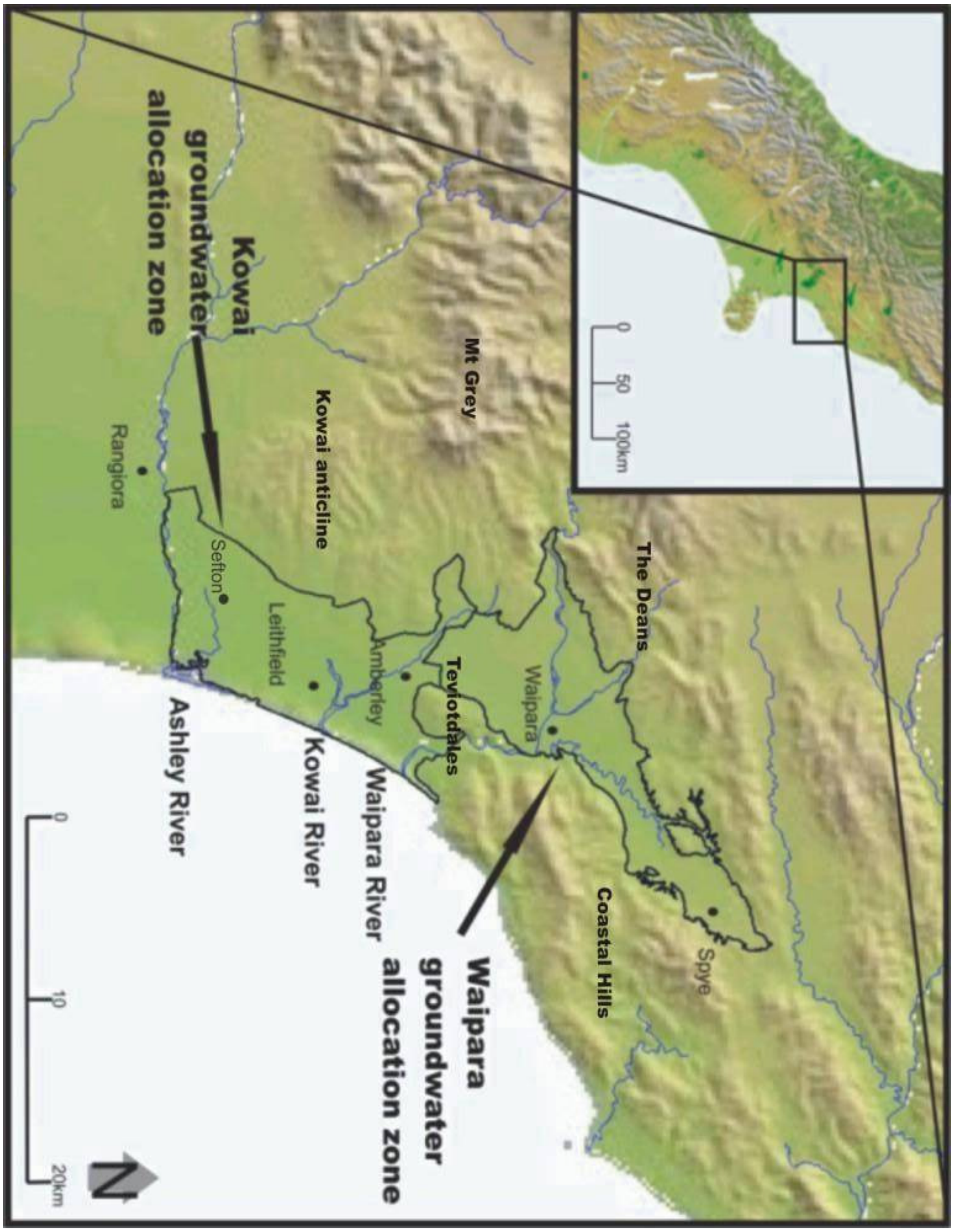

Figure 1.1Location map of the study area. Insert shows approximately the location of the study area within the South Island of New Zealand.

The history of land use in the Waipara zone illustrates the recent intensification and changing pattern of land use. These together with climatic factors and restricted catchment areas of the major river systems, can cause the allocation of limited water resources to become an urgent issue. The following review sets out this background and the nature of the problems being addressed in the objectives of this thesis.

1.3 Objectives

A number of scattered observations and new data has focused attention on the Waipara Basin suggesting that the subsurface structure may be more complicated that a simple synclinal basin and that groundwater flow and recharge patterns may require revision of the present conceptual models. If this is the case then management strategies may need to be revised and focused on smaller parcels within the broader zones. In the Kowai zone it is clear that the slopes leading down to the coast from the hills underlain by the Kowai Anticline consist of a series of broad sloping surfaces separated by obvious scarps representing several geomorphic events during general Quaternary uplift. These have not been properly recognised, documented, or dated. The age, underlying sediments and origins of these surfaces affects the nature of surface and subsurface water flow and retention.

Key observations suggest that the present models may need revisiting, giving rise to several questions.

- Anomalously old ^{14}C groundwater dates from two relatively deep wells (>60 meters beneath ground level (mbgl)) in 2007 provided ages of 1.3 ka ± 0.3 ka and 7.1 ka ± 1 ka and from localities close to the basin margins, not from the supposedly deepest central axis of the Waipara Basin as might be expected if old water had pooled at depth. These ages suggest slower recharge to the deeper wells than previously recognised, suggesting a more complicated groundwater system and raising the issue of possible mining of water.
- Weeber (per com. 2008) has described sediments from wells near the point where the Waipara River exits the basin through the lower Waipara Gorge cut into the emerging folds of the Coastal Hills. These form a bedrock sill and well sediments are suggestive of ponding and swamp or lake deposits coeval with the Canterbury aggradation gravels, having implications for the marked facies variations within this important formational aquifer.
- Uplift and emergence of gravels older that the Canterbury gravels at the Mound (Nicol et al. 1994) and propagation of the Onepunga Anticline and the associated

Bobbys Creek Fault, known to be seismically active in the late Holocene (Nicol, 1991. Nicol and Campbell, 2001) is clearly propagating across the floor of the basin deforming the Canterbury surface and uplifting older gravels surfaces on its flanks. These suggest that significant barriers may be dividing the floor of the Waipara Basin into sub basins during the Quaternary deposition with implications for aquifer geometry and water flow paths. If the recently recognised fault scarp right across the floor of the Southern part of the basin reflects a significant amount of uplift at deeper levels that may partially separate the catchment of the Kowai River and its recharge from that of the Waipara River.

- The influence of Quaternary sea-level fluctuations on the coastal deposits and estuarine reaches of the rivers needs to be integrated into the depositional model.

The issues reviewed in the preceding sections draw attention to the need to consider the water resources in the two zones by looking more closely at the evolution of the region as a whole. This includes taking into account the information from the basin margins and river catchments, as well as the basin and coastal groundwater resources which attention has been confined to in the past, to establish the tempo of events and likely influences on the subsurface geometry and deposits.

The primary purpose of this thesis is to identify sources, flow directions, quantities and the spatial and temporal variability of water recharging the Waipara - Kowai zones.

Secondary objectives leading to this primary goal include;

- producing a geomorphic map on which to base an interpretative history of the landscape;
- identifying and describing any obvious tectonic structures within the study area;
- combining this information together with additional geochemical data and well bore logs to produce a realistic conceptual hydrogeological model;
- to assess the appropriateness of the current boundary between the Waipara and Kowai zones.

1.4 Land use

1.4.1 Waipara zone

In order to determine changes in land use in the Waipara Basin a simple land use map was produced and compared with early maps (Lloyd, 2002. Figure 1.2). The map was created in ArcGIS by using 1:7500 ortho-photographs (flown 2004/2005), the author's field notes (to include changes to land use since 2004/2005), land parcel information, Environment Canterbury's Groundwater and Surface water consents layers and the AgriBase™ layer. Land use was divided into six fundamental categories, with a single category subdivided to give a total of seven categories (Figure 1.2 and Table 1.1). A predominant land use was identified and assigned to a land parcel or total farm area. As such it may overestimate the total area of any given land use.

Some categories mapped by Lloyd (2002) were not mapped by the author; such as bare ground (river beds), wetlands and inland water (dams and lakes).

The area mapped differs from that of Lloyd (2002) so comparing all the categories is difficult. However, as most (>95%) identified horticultural and irrigated pastoral land occurs on the basin floor it is possible to compare them and to calculate changes over time (Table 1.2). While the method used here will overestimate the land use actual area, it is clear that there has been a significant increase in horticulture (mainly vineyards and olive groves) and in irrigated pasture.

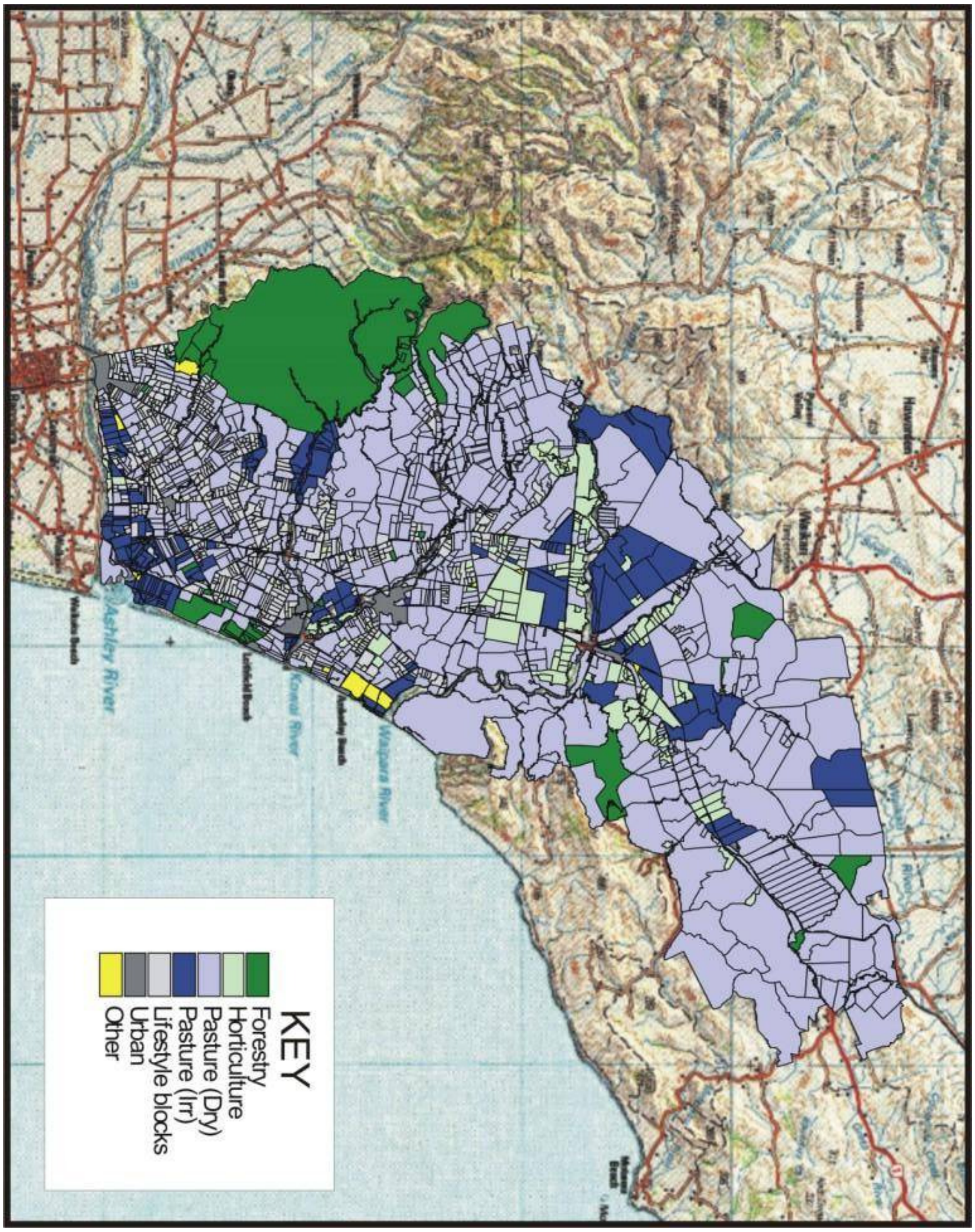

Figure 1.2 Land use classification. See text for explanation.

Table 1.1 Land use categories, category criteria and a comparison to categories used by Lloyd (2002).

Land use category	Subcategory	Criteria	Lloyds (2002) categories
Horticulture		Vineyards, Olive groves, Orchards, Plant Nurseries, Flower growers etc. NB Usually irrigated.	a) Olive groves b) Vineyards
Pasture (Irrigated)		Predominately pastoral land. Active consent to use or take groundwater or surface water.	c) Irrigated other d) Lifestyle blocks
Pasture (Non-irrigated)		Predominately pastoral land. Total farm area >25ha, without an active consent to use or take groundwater or surface water.	e) Prime pasture f) Tussock and native pasture
	Lifestyle blocks	Predominately pastoral land. Total land area usually <25ha or identified as a Lifestyle block by Agribase™, without an active consent to use or take groundwater or surface water.	g) Lifestyle blocks
Forestry		Land area predominately covered by trees or scrub.	h) Scrub i) Indigenous forest j) Planted forest k) Willows
Urban		Significant settlements/ towns.	l) Urban spaces
Other		Factories, cemeteries, large gravel pits, aggregate quarries, settling ponds, pumping stations etc.	m) Urban spaces n) Mine dumps o) Coastal sands

Table 1.2 Comparison of Land use within the Waipara Basin, 1976 – 2009. [*]Data taken from Lloyd (2002), [#] total area covered by both maps (2009 total area), ^ calculated as a percentage of the 2009 total area.

Land use	1976 (ha)	2001[*] (ha)	2009[*] (ha)	1976 %^	2002 %^	2009 %^
Horticulture	0	449	3106	0	1	10
Pasture (Irrigated)	41	739	4351	0	2	14
Pasture (Non-irrigated)	42681	40001	21431	Not comparable		
Lifestyle blocks	0	1377	587			
Forestry	5111	7988	482			
Urban	93	93	44			
Other	131	131	23			
Total area[#]			30024			

1.4.2 Kowai zone

Early land use and the agricultural development of the Kowai zone (Kowai County) is recorded in Fox et al. (1964) and Bowden et al. (1982). The first agricultural settlement by Europeans began after 1850 in the form of three pastoral lease blocks. By 1867 there were approximately 100 farms in the area between the Ashley and Kowai Rivers. A major port had been established at Saltwater Creek but abandoned after floods in 1868. The railway line reached the area in 1875 and encouraged development further to the West, particular Sefton and Amberley. Previously coastal settlements were county centres (Saltwater Creek etc). Ashley and Mt Thomas forest were first established after 1888. Ashley forest began to be logged commercially in 1939.

Between the late 1800's and the 1930's the large, sheep pastoral-lease blocks were broken up with the establishment of freehold blocks. Early on many of the small blocks were devoted to growing cereal crops but with the advent of refrigeration farms typically evolved into a mix of stock and crop. Dairy farming became established in the region after 1888 when a butter factory was built at Sefton. Interestingly, to this day dairy farming is still a prominent land use near Sefton.

From the 1930's through to the 1960's improvements in agricultural technology lead to a decrease in crop farming and increase in pastoral farming, particularly sheep farming.

Anecdotal evidence suggests that in recent times (<10 - 15 years) there has been a trend towards small subdivisions (average plots size 7.2 ha), lifestyle blocks and small cottage industry type activities. In particular the area referred to as the downlands by Fox et al. (1964) has been extensively subdivided. Irrigated land is confined to areas near larger creeks and rivers, and on the Ashley flood plain below Sefton. This relatively recent change from mixed crop and pastoral farming to more intensified land use of lifestyle blocks has escalated the demand for public supply water.

1.5 Climate

Sturman et al (1984) found that in Canterbury anticyclonic winds from the West were the dominate weather pattern, with anticyclonic South-Westerlies common all year round. Sturman (1986) found that precipitation in Mid-North Canterbury was dominated by Easterly systems affected by coastal hills whereas to the East of the Southern Alps both the Westerly and anticyclonic systems dominated. This is due to New Zealand's geographic location with prevailing Westerly winds and the orographic influence of the Southern Alps.

Annual mean rainfall within the study area varies from approximately 600 – 700mm at the coast to more than >1000mm at Mount Grey and >800mm along the coastal hills (Lloyd, 2002). Generally Lloyd (2002) found that there was a correlation between increasing relief and increasing precipitation.

Lloyd (2002) using rainfall records from 32 sites across his field area showed that there was little variation in average monthly rainfall throughout the year. However, minimum and maximum values indicate that there was significant variation around the mean.

Actual evapotranspiration (aET) has been estimated by Horrell (1992), Lloyd (2002) and Chater (2002). Generally there is a strong seasonal trend where on average aET exceeds rainfall during the Summer resulting in significant soil water deficits.

1.6 Hydrogeology and hydrology

1.6.1 Previous hydrogeological work

The first region-wide hydrogeological investigation in the Waipara Basin was conducted by Loris (2000). Loris (2000) used chemical, geophysical and hydrogeological methods to define alluvial aquifers, their characteristics and recharge sources to produce a conceptual model of the basin (Figure 1.3). This shows the basin as a single elongated trough formed by the Waipara syncline, lying between the uplifted coastal ranges and the Easterly dip slopes of the Deans bordering the hinterland ranges. This work was followed by Lloyd (2002) who focusing on the Waipara River Catchment (surface water and groundwater resources). He described the climatic conditions in the basin (rainfall and evapotranspiration), hydrology and groundwater recharge. Lloyd (2002) produced a detailed water balance for the catchment and a conceptual model (Figure 1.4).

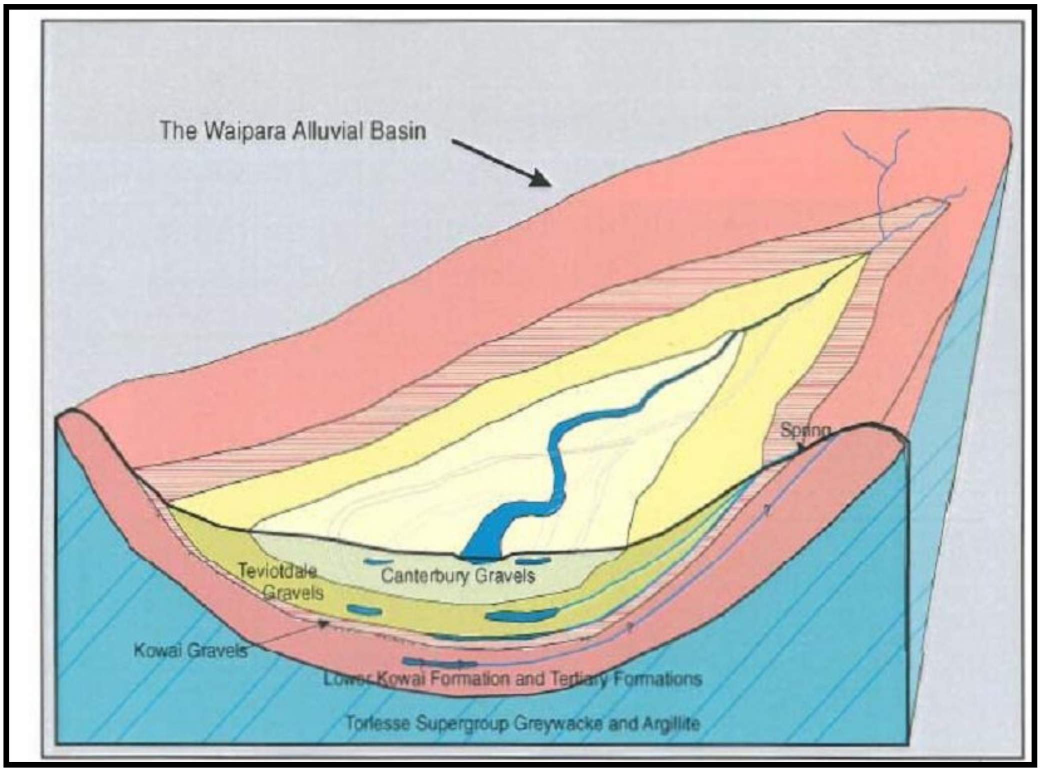

Figure 1.3 Hydrogeological model of the Waipara Basin from Loris (2000).

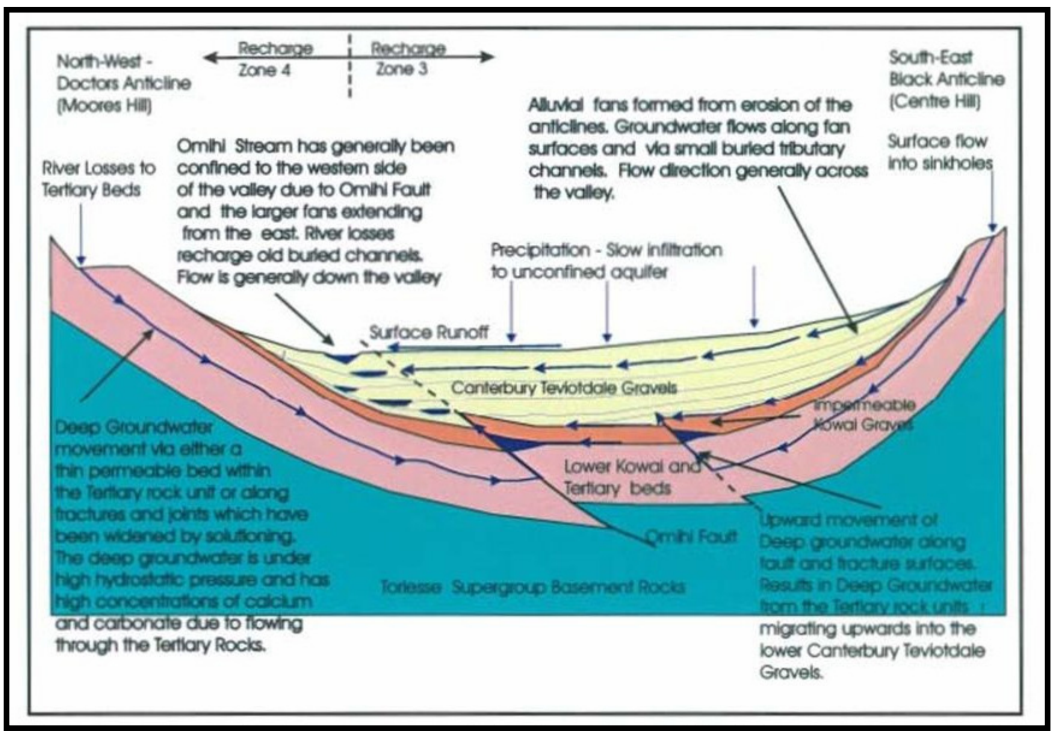

Figure 1.4 Conceptual model for recharge to the Omihi valley, Lloyd (2002).

Armstrong (2000) and Finnemore (2004) used geophysical methods in the Culverden basin and Omihi valley, partly to obtain information about the groundwater systems. Armstrong (2000) developed the hypothesis that emerging structures within the Culverden basin progressively partitioned the basin, localising the distribution of the younger gravel units which may influence groundwater flow. Finnemore (2004) found that in the Omihi valley ongoing tectonic deformation from the Omihi fault affected the distribution of infilling alluvial sediments resulting in the Omihi Stream being confined to the Eastern margin of the valley. Finnemore (2004) concluded that buried channels from the Omihi Stream were promising targets for productive water wells. Both these studies draw attention to the role of tectonically active structures propagating beneath these basins as they evolve, controlling the depositional environment and influencing groundwater flow paths.

Groundwater investigations in the Kowai zone have been targeted at specific problems. In 1981 J Weeber (per com. 2008) conducted an investigation into the geology and groundwater flow directions following concerns raised by the Hurunui District Council about a proposal by Canterbury Timber Products, Sefton, to discharge effluent from the timber mill located up gradient from a public supply well. Callander (1988) investigated stream depleting bores linked to the lower Ashley River. Callander (1989) estimated the volume of groundwater contained within the lower terraces of the Kowai River (NB) to resolve a consent dispute. Main (1992) looked at surface water and groundwater quality using a very limited data set to determine potability. Moore (1995) conducted a hydrochemical investigation into potential saltwater intrusion at Amberley beach, ultimately concluding that the high chloride levels in the wells were caused by salt spray. Pattle Delamore Partners Ltd (PDP) (2001) conducted an investigation into the occurrence of arsenic in surface water and groundwater in the area between Saltwater Creek and Woodend (to the South). PDP (2001) concluded that there was no obvious spatial pattern to arsenic detection in groundwater, but it is likely to be related to organic rich sediments which chemically reduce groundwater and allow contaminants to mobilise. Aitchison-Earl (2004) estimated stream depletion of the Ashley River and tributaries.

1.6.2 Groundwater allocation zones

Groundwater allocation zones were first introduced to Canterbury in 2004. Initially two methods were proposed to calculate ground based recharge; 15% of the average annual rainfall and 50% of the land-surface recharge (Aitchison-Earl et al, 2004). Initially the Waipara zone allocation was determined by the 15% annual rainfall method. The Waipara zone allocation was reassessed by Aqualinc Research Ltd (2005) using the land-based recharge method. Later Weeber (2006) redefined the area using the latest geological map from the University of Canterbury and a new allocation limit was determined. The land-based recharge estimate for the Kowai zone was determined by Aitchison-Earl et al (2004) and then Scott (2004).

1.6.3 Previous hydrological work

The first significant work in the Waipara region was conducted by Horrell (1992) who produced a rainfall and mean annual flow isohyet map. Loris (2000) conducted limited river gaugings to estimate losses from the Waipara. Lloyd (2002) carried out extensive surface water gaugings on the Waipara River and selected tributaries to estimate losses to groundwater. Chater (2002, 2003) built on earlier hydrological work and produced a mean flow and a seven day low flow isohyet map. Scarf (2007) recently updated the seven day low flow isohyet map.

The Ashley River and catchment was thoroughly described by Bowden et al (1982). This report calculated mean annual flows and produced estimates of rainfall and potential evapotranspiration. Chater (2004) estimated seven day low flows and estimated losses and gains to the groundwater system.

1.6.4 River system characteristics

The major hydrological systems in the study area are the Waipara River, Ashley River and the Kowai River (Figure 1.1). The catchment area and mean flows for these rivers are shown in Table 1.3.

Table 1.3 demonstrate that the major rivers within the study area have relatively small catchment areas and mean flows. The catchments of these rivers drain the foothill area of the Canterbury Plains. These rivers have little storage (Lloyd, 2002. Chater, 2002, 2004) and receive rainfall from Easterlies and occasional Northwesterly spill over (Sturman, 1986). In comparison the Waimakariri and Waitaki Rivers catchment areas extend to the divide between the West and East coasts and have extensive storage (snow, lakes etc).

Table 1.3Catchment areas and mean flows from the major rivers in the study area. Also shown are the Waitaki and Waimakariri catchments for comparison.

River	Catchment area (km^2)	Mean flow	Comments
Waipara	370	3.0	Site: White Gorge recorder (near the Deans in Figure 1.1). Source ECan (2009)
Kowai (NB)	72	0.3	Site: Greys Road near Amberley. Source per com. A Martin (2009)
Kowai (SB)	87	0.1	Site: Mt Grey (mean of all gauging data)
Ashley	121	3.9	Site: Lee valley. Source ECan (2009)
Waimakariri	3210	122.0	Site: Old Highway Bridge. Source ECan (2009)
Waitaki	9760	373.0	Site: Kurow. Source ECan (2009).

1.7 Groundwater use and development

Loris (2000) described how water was used in the Waipara Basin from the about the turn of last century onwards. It is assumed that a similar groundwater development is applicable to the Kowai zone, in that for most of the last century wells were dug for domestic and stock water purposes, albeit with a small number of irrigation wells. From the seventies onwards there was an increase in the total number of wells drilled (Figure 1.5). Dodson (2006) found in the Mayfield – Hinds region that spray irrigation began to be applied in the seventies increasing significantly to the present. In the Waipara and Kowai zones it seems that the most significant increase in demand occurred in the 1990’s. There is a limited record of actual irrigation usage data in Canterbury.

From 2004 onwards a groundwater allocation limit has been defined for selected regions to assist with management of the resource (Aitchison-Earl et al, 2004). The limits for both zones have changed on at least one occasion as different methodologies have been applied, or new information has been obtained. Since November 2004 the allocation limit for Kowai has not changed. For the Waipara zone however there has been a more complex allocation limit history, but for the sake of simplicity in Table 1.4 only a single limit is shown.

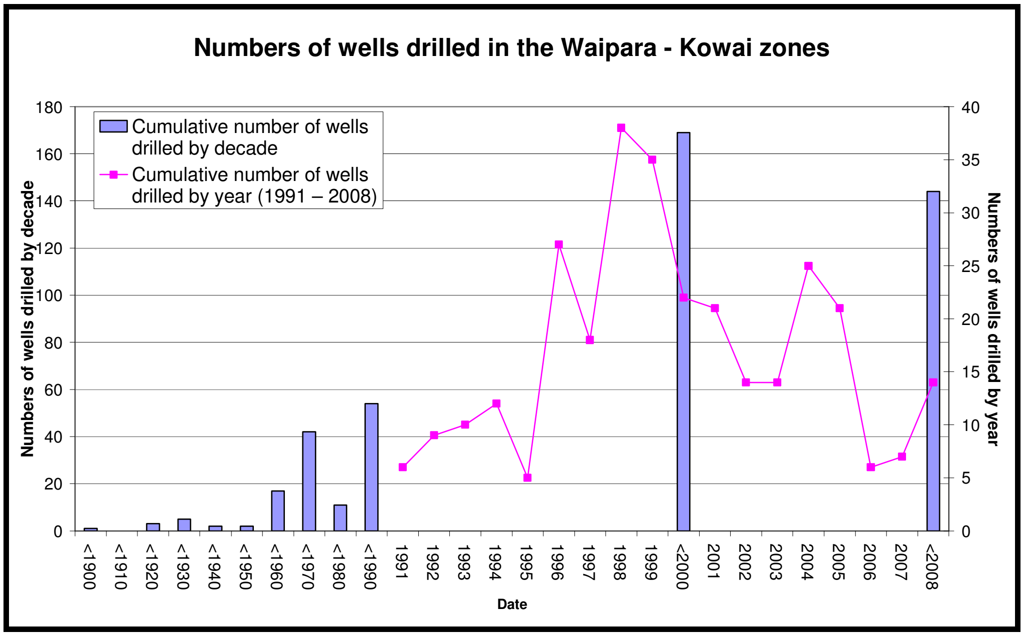

Figure 1.5 Wells drilled by decade (1900 - 2008) and by year (1991 - 2008) as recorded in Environment Canterbury's wells database.

Table 1.4 is an attempt to estimate the demand and usage for groundwater in the Waipara - Kowai zones. The issued annual volumes are estimates retrieved from Environment Canterbury's consents database or taken from Aitchison-Earl et al (2004). The estimated usage is calculated by assuming 60% of the annual consented volume is used in any given year. The 60% assumption is based in part on work conducted by Sanders (2000) who indirectly estimated usage from electricity demand and also measured a small number of irrigation takes from farms on the Canterbury Plains. The figures shown in Table 1.4 must be considered a very crude estimate given that it assumes all takes are exercised, that public supplies are likely to use close to 100% of their consented take all year round and the volume used for irrigation takes will vary depending on the climatic conditions of any given irrigation season.

It is clear from Table 1.4 that there has been a significant increase in issued groundwater consents in the Waipara zone and as such there is likely to be an increase in abstraction. In the Kowai zone there has been little change in issued groundwater consents except between 2004 and 2005. It is suspected that the estimate used by Aitchison-Earl et al (2004) was too high or alternatively during this period consents were surrendered or expired.

Table 1.4TOP Summary table of allocation limits, an estimate of issued groundwater annual volumes and changes of groundwater issued volumes through time. BOTTOM an estimate of usage using the 60% usage assumption for all takes (including public supplies) and comparison of estimated usage to the allocation limit through time. * Estimates taken from Aitchison-Earl et al (2004).

	Allocation limit		Issued		Δ change issued	
	Wai	Kowai	Waipara	Kowai	Waipara	Kowai
			Estimated annual volume			
as of	m^3 x 1 000 000		m^3 x 1 000 000		%	
10/2004	10.7	17.4	6.3*	9.2*		
12/2005	10.7	17.4	6.5	5.6	2.2%	-21.0%
12/2006	10.7	17.4	7.4	5.6	7.9%	0.0%
12/2007	10.7	17.4	8.0	5.6	5.7%	0.4%
12/2008	10.7	17.4	9.1	5.5	10.0%	-0.9%
02/2009	10.7	17.4	9.3	5.5	2.0%	0.0%

	Waipara	Kowai	Waipara	Kowai
	Estimated usage 60% x Issued		Estimated usage/ allocation limit	
	m^3 x 1 000 000		%	
10/2004	3.8	5.5	35.3%	31.7%
12/2005	3.9	3.3	36.7%	19.1%
12/2006	4.4	3.3	41.4%	19.1%
12/2007	4.8	3.4	44.8%	19.4%
12/2008	5.4	3.3	50.8%	18.8%
02/2009	5.6	3.3	52.0%	18.8%

From this overview it is evident that in the Waipara Basin the available data indicates an increasing demand for water in a basin where during the spring and summer the modest rainfall is insufficient to maintain soil moisture at a level to support horticulture and intensive pastoral use. It may be insufficient to recharge groundwater to levels able to meet the demands for irrigation. Streams and rivers entering the basin have modest catchments limited to the foothills area and cannot be certain of adding sufficiently to the recharge. Groundwater takes in the Kowai zone are restricted to the areas of low lying coastal and river floodplains and in general have been the subject of much more limited investigation.

To understand the movement of water through both areas and to evaluate the capacity of the aquifer systems the geological setting, and in particular the Quaternary evolution of this landscape, needs to be brought together both as a regional synthesis of previous work and in more detail than is currently available.

1.8 Geology and tectonic setting

1.8.1 Previous work

There have been a large number of Geological studies completed in or near the Waipara and Kowai zones. Early studies focused on stratigraphy and structural and geological mapping (Andrews, 1963. Wilson, 1963 (and references within). Carr, 1970. Hoolihan, 1978. Katz, 1982. Harris, 1982. Browne and Field, 1985. Yousif, 1987. Nicol, 1991. Mcpherson, 1991. Cowan, 1992. Litchfield, 1995). More recently geophysical and tectonic investigations have been carried out to determine subsurface structure using a variety of methods (Barnes, 1993. Armstrong, 2000. Loris, 2000. Finnemore, 2004. Duffy, 2008). Paleoseismic investigations have been carried out on a number of faults to the South and Southwest of the study area to help determine the seismic risk to the region (Sisson, 1999. Howard, 2001. Estrada, 2003). Interactions between geomorphic and tectonic processes have been investigated along the Waipara River (Nicol et al, 1994, Nicol and Campbell, 2001).

1.8.2 Regional geological setting

New Zealand straddles the boundary between the Pacific and Australian plates. To the North the Hikurangi trench marks the subduction of the Pacific plate beneath the Australian plate. In the South the Puysegur trench marks the subduction of the Australian plate beneath the Pacific plate. Relative plate displacement rates decrease Southwards from 50mm/yr in the North to 30mm/yr to the South (Figure 1.6).

In the South Island the Alpine Fault accommodates a significant amount of this strain (>75% according to some estimates, Norris et al (1990)). The Marlborough Fault Zone (MFZ) is thought to transfer strain from the Alpine Fault to the Hikurangi trench (Figure 1.6). The MFZ is composed of a series of predominantly strike slip and oblique slip faults that are interpreted to have formed progressively Southwards with the Hope Fault being considered the most recent fully developed member. Tectonic and paleoseismic studies suggest that the Hope Fault is the most active fault in this system (Van Dissen and Yeats, 1991. Pettinga and Campbell 2000. Langridge et al. 2003). Located to the South of the Hope Fault, on the margins of the Canterbury

Plains is the Porters Pass – Amberley Fault Zone (PPAFZ. Cowan, 1992). The PPAFZ is though to be the juvenile member of the MFZ.

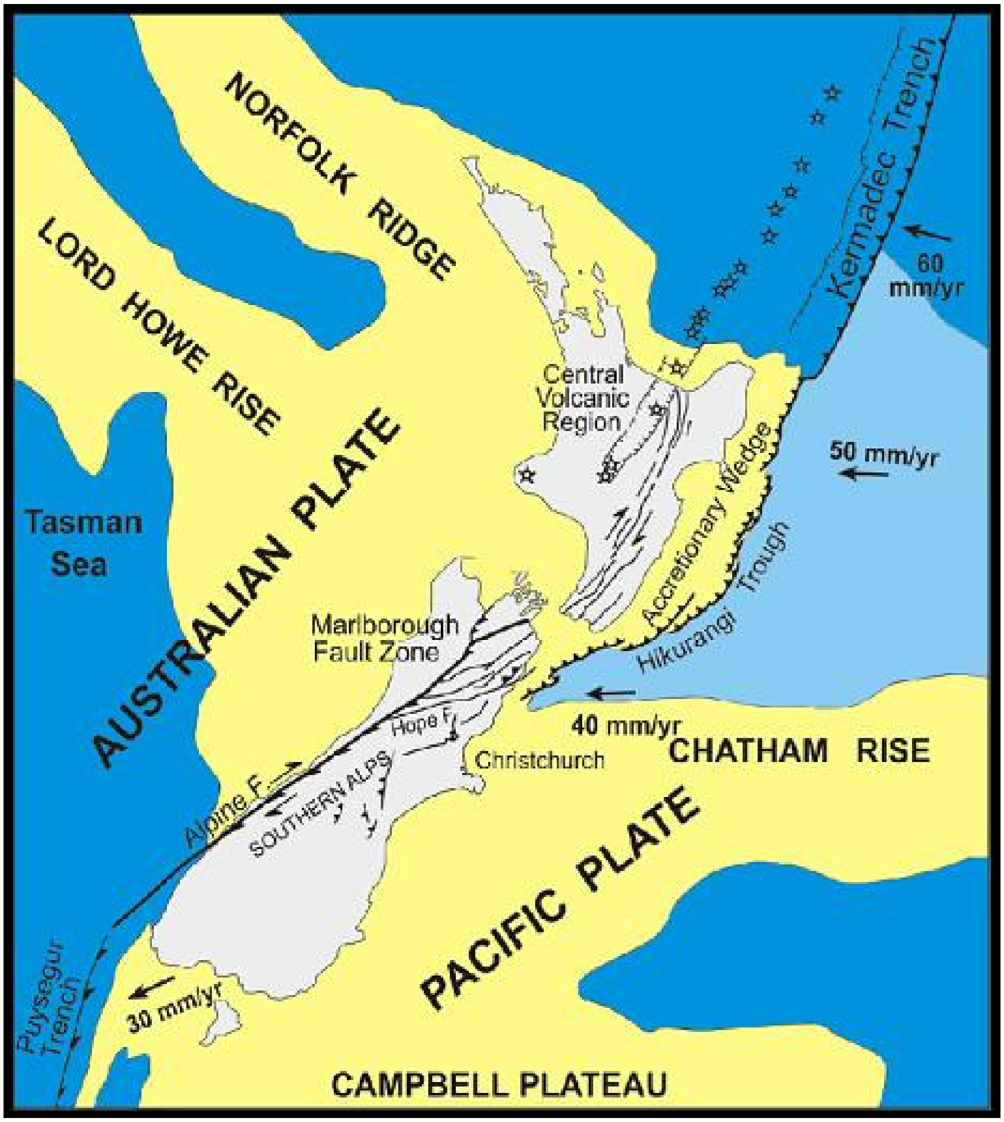

Figure 1.6 Regional geological setting of New Zealand. Yellow indicates submerged continental crust, blues indicate oceanic crust. Plate vectors adapted from DeMet et al 1990. The study area is 50 km North of Christchurch. Source J Pettinga

The deformation within the Canterbury and the Southern Alps has been interpreted as representing a two sided wedge prograding from a mid – lower crustal detachment fault (Norris et al, 1990. Pettinga et al, 2001. Figure 1.7). This model depicts low angle faults at depth that steepen towards the surface. Of note are the Alpine Fault and the emerging thrust faults beneath the Canterbury Plains (to the Southeast of the Alpine Fault).

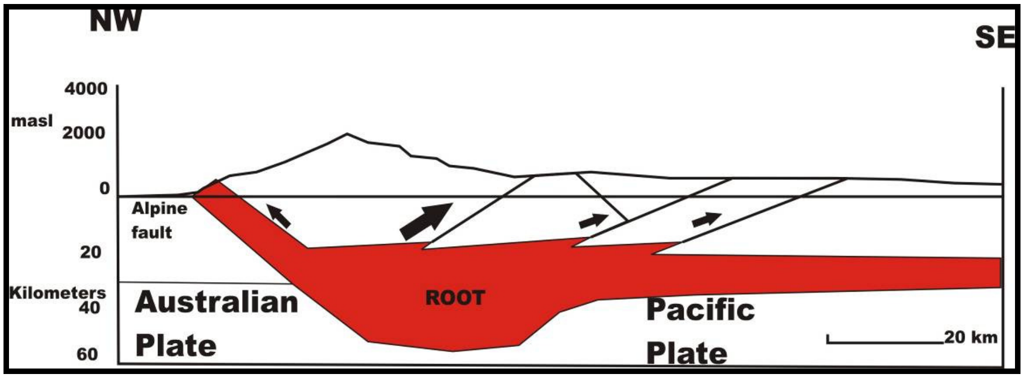

Figure 1.7 Schematic section of the Southern Alps, South Island, New Zealand. Adapted from Norris et al 1990.

The study area is located at the Southern margin of the MFZ where it is affected by the strike-slip shearing of the PPAFZ interacting with the thrust fault systems generated by the plate convergence. The tectonic deformation of the Canterbury region has been classified into a series of structural domains (Pettinga et al, 2001. Figure 1.8). The study area is within domain four and within the vicinity of domains two, three and seven.

Typically Domain four (North Canterbury Fold and Thrust belt) is dominantly North-East trending, Easterly dipping thrust faults. Yousif (1987) found these faults were related to asymmetrical growing folds with a transpressive sigmoidal form in the region of the PPAFZ near the coast. These structures occur in the North-East of the Canterbury region and offshore across the continental slope and shelf (Barnes, 1993). These faults are typically identified as forming topographic ridges with synclinal basin floors and onshore general thrust basins such as the Waipara Basin. Pettinga et al (2001) proposed that this domain is responding to "*oblique plate convergence and the transition from subduction related tectonics in the North, to oblique continental – continental collision West of the Chatham Rise*".

Domain seven contains a series of hidden North–Northeast trending active faults and folds. These faults are prograding up through the Quaternary fluvial deposits of the Canterbury Plains but some are yet to emerge to the surface. Pettinga et al (2001) attributed these faults to tectonic shortening, crustal thickening and uplift. Domain three contains hybrid interconnected system of East–Northeast trending oblique transform, strike-slip, reverse faults with fault propagating folds. This domain encompasses the PPAFZ. Domain two contains Westerly dipping thrust faults and associated folds. The structures in this domain are interpreted as back thrusts from the Alpine Fault Zone (Figure 1.8).

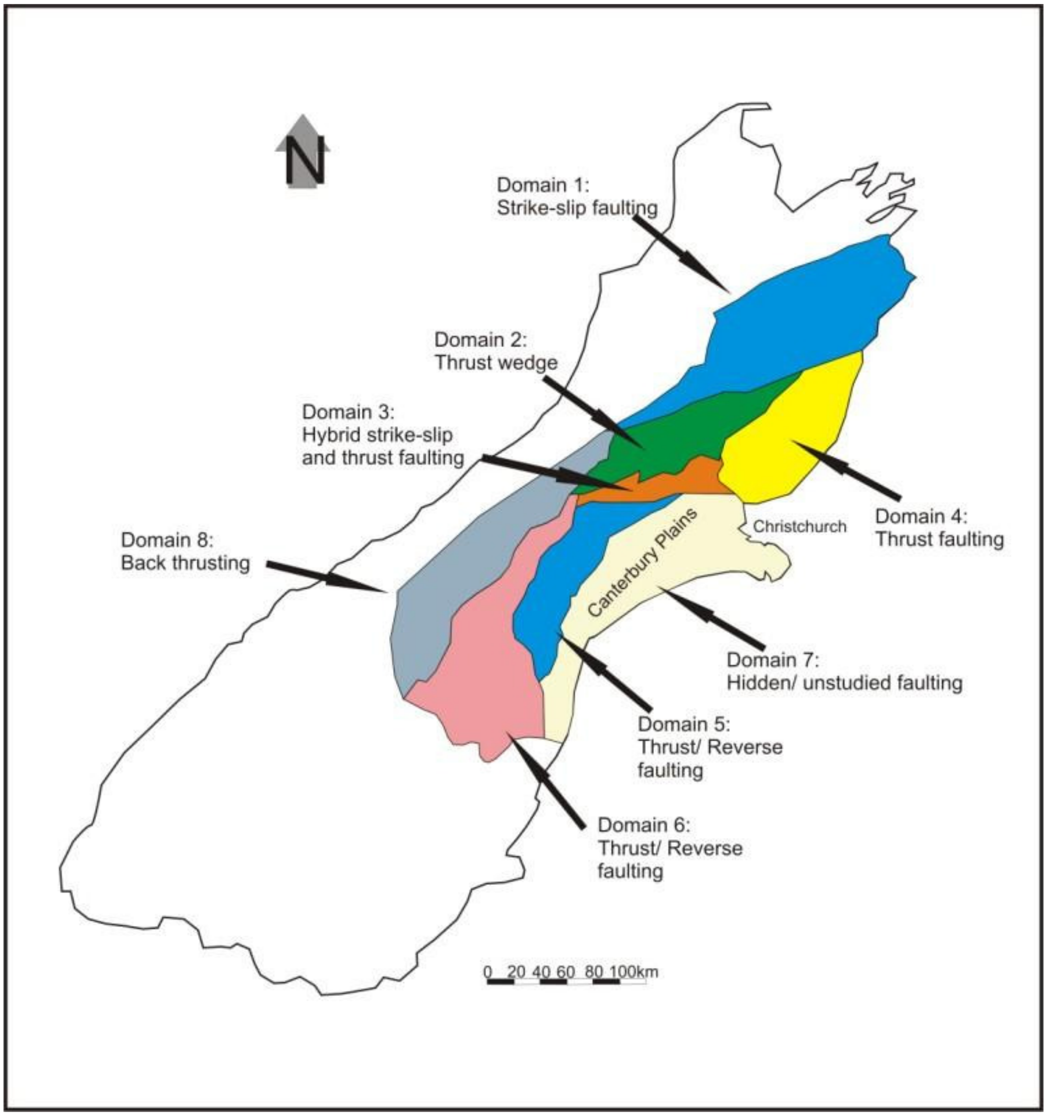

Figure 1.8 Structural domains within the Canterbury region (modified from Pettinga et al. 1998, 2001).

The emergence of this fold and thrust belt deforms the basement and Cretaceous Tertiary cover sequence and is the youngest part of both the MFZ and the migrating thrust systems generated by the plate convergence. Thus the pre-Pleistocene stratigraphy reflects the older, more regional basin sequences, whereas the Quaternary stratigraphy is strongly influenced by the local tectonics and Pleistocene climatic controls. Regional crustal shortening and uplift lead to the erosion and emergence of the basin margins. This leads to reworking of the basin contents, reflecting the local influences on facies and onlap, or offlap relationships.

1.9 Stratigraphy

Figure 1.9 is a generalised stratigraphic column adapted from Nicol (1991) taken here as representative of the Waipara region. Figure 1.9 is based on work by Nicol (1991) and Browne and Field (1985). Map A (complied by the Geology department, University of Canterbury) is the most recent geological map of the Waipara Region (pocket).

1.9.1 Basement

The basement rocks throughout Canterbury are those of the Mesozoic Torlesse Super group. These rocks are composed of alternating quartzo – feldspathic sandstones and argillite, rare conglomerates, chert, volcanics and limestones (MacKinnon, 1983**.** Cowan, 1992. Adams and Maas, 2004). In the study area Torlesse Supergroup rocks outcrop in the cores of Anticline that ring the Waipara Basin. These sediments outcrop extensively to the East-Northeast of the study area in the upper catchment areas of the major rivers due to continuing tectonic deformation.

Depth to basement has been estimated in the Waipara Basin by Loris (2000) using gravity geophysical methods. In the Northern part of the basin near Spye the depth was estimated at 800 – 1000m, further North along Georges Road (near the Waipara River) the thickness was estimated to be 1000 – 1500m. Kowai–1 sited on the Kowai Anticline intercepted 1400m of cover sediments[1] before striking Torlesse Supergroup sediments (Hoolihan, 1978).

[1] Some of the units intercepted were steeply dipping. Therefore 1400m is a minimum thickness for this sequence.

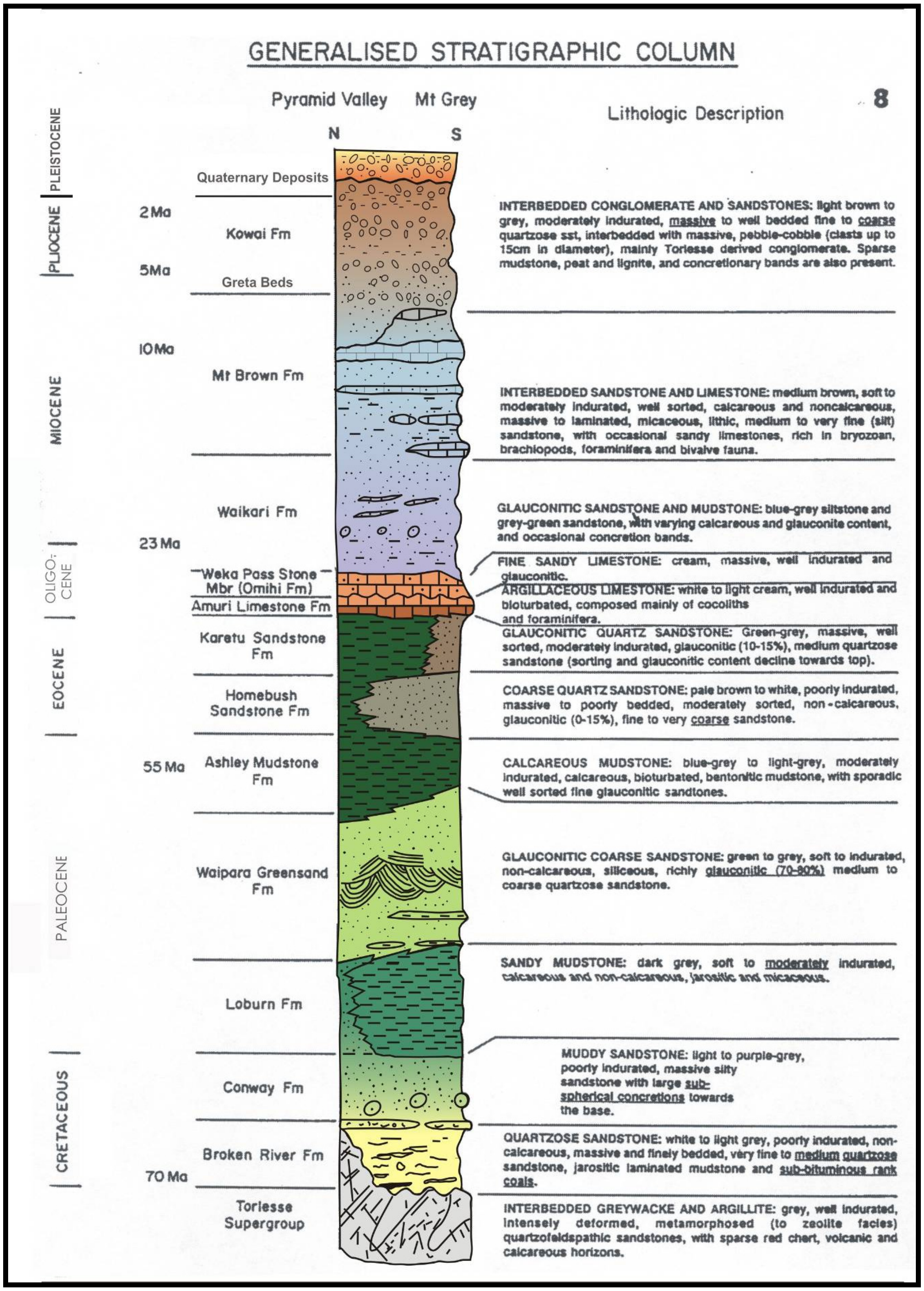

Figure 1.9Generalised stratigraphic column, from Nicol (1991).

1.9.2 Cover sediments

The cover sediments consist of a thick sequence of mudstones and sandstones with three prominent limestone units. The sequence represents a general major marine transgression – regression. The thickness of this sequence recorded in the Kowai-1 bore is in the order of 450m thick. To the North in the middle Waipara gorge preserved cover sediments are in the order of 1000m thick (Nicol, 1993). Locally these sediments are thin to absent particularly on the limbs of active faults and folds. The mudstones and sandstones of the region are often associated with varying amounts of glauconite and calcium carbonate. Browne and Field (1985) wrote that the Amuri Limestone was composed of 60 – 97% calcium carbonate, with an average of 79% (n=137). Weka Pass stone has a calcium carbonate content of 67 – 77% (Thompson, 1920 as sited in Andrews, 1963). These rocks can influence the chemistry of the water flowing into the adjacent basins and are recycled into the younger basin sediments.

1.9.3 Structure and Quaternary deposits of the Waipara – Kowai zones

The Waipara Basin is a Southward plunging syncline flanked by the Doctors Range and Coastal Hills. Yousif (1987) mapped the Coastal Hills as a series of Northeast trending sigmoidal asymmetrical fold and thrust faults exposing basement rocks at the core. The Omihi Fault is located on the Western margin of the Coastal Hills, emerging on the Eastern side of the basin (Harris, 1982. Finnemore, 2004). Doctors Range and the upper Waipara gorge were formed by the Eastward facing Karetu thrust and the anomalous East-West trending Boby's Creek oblique strike-slip fault (Nicol, 1991). Boby's Creek Fault is associated with the Onepunga Anticline that protrudes Eastward into the basin where it is covered by Quaternary gravels offlapping as successively younger aggradation surfaces. The Doctor's Range Anticline has Torlesse Supergroup at it core exposing East dipping Tertiary sediments giving rise to the impressive stratigraphic section and topographic features the Waipara gorge is renowned for.

Within the Waipara Basin there is evidence for two emerging structures within the basin; the Mound Fault (Nicol et al. 1994) a West facing thrust and associated Anticline and a low fault scarp striking Southwest across the Southern half of the basin about which little is known. Loris (2000) and Finnemore (2004) inferred other developing structures within the Northern Omihi area of the basin that are yet to emerge to the surface.

The dominant features surrounding the Kowai zone are the Kowai Anticline and Mt Grey thrust fault (Hoolihan, 1978. Katz, 1982. Cowan, 1992). The Kowai Anticline is a Northeast trending feature which is related to the development of the PPAFZ and as such likely to be an active structure. At the core of the anticline, Tertiary sediments are exposed (Cowan, 1992). The Mt Grey thrust fault has thrust Torlesse Supergroup (to the Southeast) over Quaternary gravels.

To the Southwest of the study area there are a series of structures emerging from beneath the Canterbury Plains; Springbank Fault, Loburn and Ashley Faults (Cowan, 1992. Sissons, 1999. Estrada, 2003).

1.9.4 Pliocene – Holocene sediments

Within the Waipara Basin there are five recognised Pliocene – Quaternary formations being (Wilson, 1963. Harris, 1982. Nicol et al, 1994); Kowai Formation, Teviotdale gravels, Canterbury gravels, Omihi gravels and Weka alluvial fan.

The Kowai Formation is strictly the uppermost regional unit of the cover sequence and consists of marine – terrestrial sediments which marks the emergence of the New Zealand landmass after the onset of the Kaikoura orogeny. It is included here because it marks the uppermost unit predating the evolution of the local structures and defines the base of the overlying unconformable sequence of the basin fill units. It is also important as it marked a former Pliocene or early Pleistocene shoreline passing through this area. The marine portion of the Kowai Formation consists of fossiliferous sandstones, sandy mudstones and conglomerates (Browne and Field, 1985). The terrestrial component of the formation (the Kowai gravels) consists of gravels with sand and silt lenses (Wilson, 1963). The distinguishing feature of Kowai gravels is the highly weathered and rounded nature of the clasts implying a more distant source than the immediate basin margins and predates the emergence of the local range structures. The maximum thickness of this formation is likely to be in the order of 650m (Browne and Field, 1985).

The Teviotdale gravels discordantly overly the Kowai Formation and consist of gravels with sand beds and sand or silt lenses. This unit has a distinctive creamy-brown colour (Wilson, 1963, Figure 1.10). The gravel clasts are typically slightly to moderately weathered, however it commonly contains Kowai gravel clasts. No units between the Kowai gravels and the Teviotdale Formation have been identified although this represents a significant interval of lower Pleistocene time that is unrepresented.

Figure 1.10 Photography showing the Canterbury gravels (top grey unit) and Teviotdale Formation (bottom orange – brown unit). Photography taken near the Waipara River at Grid M34:835-934.

The younger Canterbury gravels consist of gravels with lenses of silt and sand (Figure 1.10). This unit is light gray in colour and the clasts are un-weathered but it also contains common Kowai gravel clasts. It underlies the youngest late Pleistocene aggradation surface although that surface is commonly degraded and modified.

More locally, the Omihi gravels were first described by Harris (1982) and they are essentially fine sands, silts and clays with occasional gravel lenses associated with the meandering Omihi Stream and fans formed from the topography. The Weka alluvial fan is mapped in Nicol et al (1994) and is associated with the Weka Creek. Late

Holocene coastal deposits are associated with young progradation of the coastline (Shulmeister and Kirk, 1993).

Uplifted interglacial marine terraces have been described by Carr (1970) and Yousif (1987) along the coast North of the Waipara River mouth, and while these lie immediately outside the study area they are important indicators of the amount of late Quaternary uplift of the coastal ranges and lower Waipara Gorge. They also constrain the age of the Teviotdale surface aggradation events as younger that the last interglacial.

The Quaternary deposits in the Kowai zone were initially mapped by Gregg (1964). Portions of the study area have more recently been mapped by Bowden et al. (1982), Weeber (1981) and Mcpherson (1991). These deposits consist of glacial and interglacial terrestrial and marine deposits. The deposits are though to be equivalent to the stratigraphic formations of Brown and Wilson (1988).

It should be noted that there is no evidence that the Quaternary alluvial units in the study area formed directly from the ice front. Rather, it is assumed they formed in periglacial conditions (Wilson, 1963).

2 Chapter two: Geomorphology and active tectonics

2.1 Introduction

The purpose of this chapter is to describe landforms and the underlying geology within the study area. This has been achieved by producing a geomorphic map (based on Landcare Research Ltd soil maps, data provided by T Webb), examining bore logs and conducting a limited soil survey of selected transects across the landscape. Three hammer and plate seismic surveys were conducted in the Waipara Basin to define tectonic structures and to gain an understanding of the gross structure within the basin. Morphometric analysis of river gradients was conducted primarily to indicate the presence of emerging tectonic structures but proved to be useful in distinguishing geomorphic surfaces. Stream channel behaviour was investigated to indicate ongoing deformation in the landscape.

2.1.1 Geomorphic mapping and subsidiary soils survey

The aims of the geomorphic mapping are (pocket, Map B) summarised:

- to improve the understanding of the development of this landscape through time;
- to estimate the spatial location, thickness and number of loess sheets in the study area on which to base a chronology;
- to identify tectonic structures within these basins and assess their influence on the landscape.

The geomorphic mapping was constructed with the aid of aerial photographs, LIDAR imagery (Appendix 2a), topographic contours, differential GPS data and 1:50 000 scale soil maps produced by Landcare Research Ltd. Landcare Research Ltd soils maps are based on previously published soil maps and additional field work with observations limited to a depth of 1m and are not directly indicative of the underlying loess or superficial deposits. Soil series have been grouped chronologically (Appendix 2b). Examination of outcrops, bore logs and the soil auguring transects were used to ground truth interpretations, establish likely loess thicknesses and constrain surface boundaries.

The limited soil survey in this study was lead by Dr. Philip Tonkin and assisted by the author. The basis for the soil descriptions is shown in Appendix 2b. A particular emphasis was paid to the presence of loess and the number and thickness of loess sheets as well as the soil types to provide a means of regional correlation of surfaces and a general estimate of chronology. Generally, loess sheets were distinguished on the basis of buried soils or identifiable B horizon features (in Pallic soils; mottling (Bg), clayey (Bt), fragipan (Bx)) or, in the case of Brown soils where no distinctive horizons can be identified (Bw, where w = weathered), thicknesses were used. Initially it was assumed that one loess sheet was <3 m thick, two sheets were <6m thick and three sheets were >6m thick. Soil survey sites were selected along four transects supplemented with a number of one-off sites (Appendix 2c). Following the completion of the soil survey it was decided to merge surfaces overlain by multiple loess sheets into a single geomorphic unit. This is because it was difficult to distinguish landforms mantled by two or more loess sheets using aerial imagery.

2.1.2 Conceptual models

It has been shown that there is a relationship between the behaviour of rivers, climate and tectonic uplift (Bull, 1991). Figure 2.1 attempts to summarise some of these processes. In the New Zealand climatic setting, river aggradation is thought to occur during glacial periods when sediment supply and stream power are greatest. Globally, as large volumes of water become entrained in glacial ice sheets, sea level drops and the fluvial aggradation surfaces grade to a lower and more distal coastline. During the subsequent interglacial period with reduction in sediment supply and stream power (partly due to increased vegetation cover), rivers will entrench into their deposits. Deglaciation of the ice caps returns vast amount of water to the ocean and sea level will rise with aggradation back filling the lower reaches of rivers. As such interglacial and glacial rivers grade to base levels at different elevations, and therefore should have different surface gradients.

Loess deposition is thought to occur during periods of river aggradation where dust from the flood plain is transported by wind and deposited downwind (Eden and Hammond, 2003). While it has been observed that loess is presently being formed and deposited along the modern Rakaia River (Ives, 1973. Berger et al, 1996) it has been proposed that most of the loess found regionally was produced during a major aggradation period which blanketed the deposits from the previous aggradation events (Bull, 1991). As such loess has been used as a climatic proxy (Alloway et al, 2007) and for the purpose of chronology. Berger et al, (2001) dated loess sheets using luminescence methods on the Cust downs (just to the South of the study area) producing results of 73 ± 13 ka obtained from near the base of the lowest Loess sheet 3 (L3), 41 ± 5 ka from near the base of L2 and 27 ± 3 ka near the base of L1. These dates are broadly consistent with other ages found for loess units (Almond et al, 2001. Litchfield and Rieser, 2005).

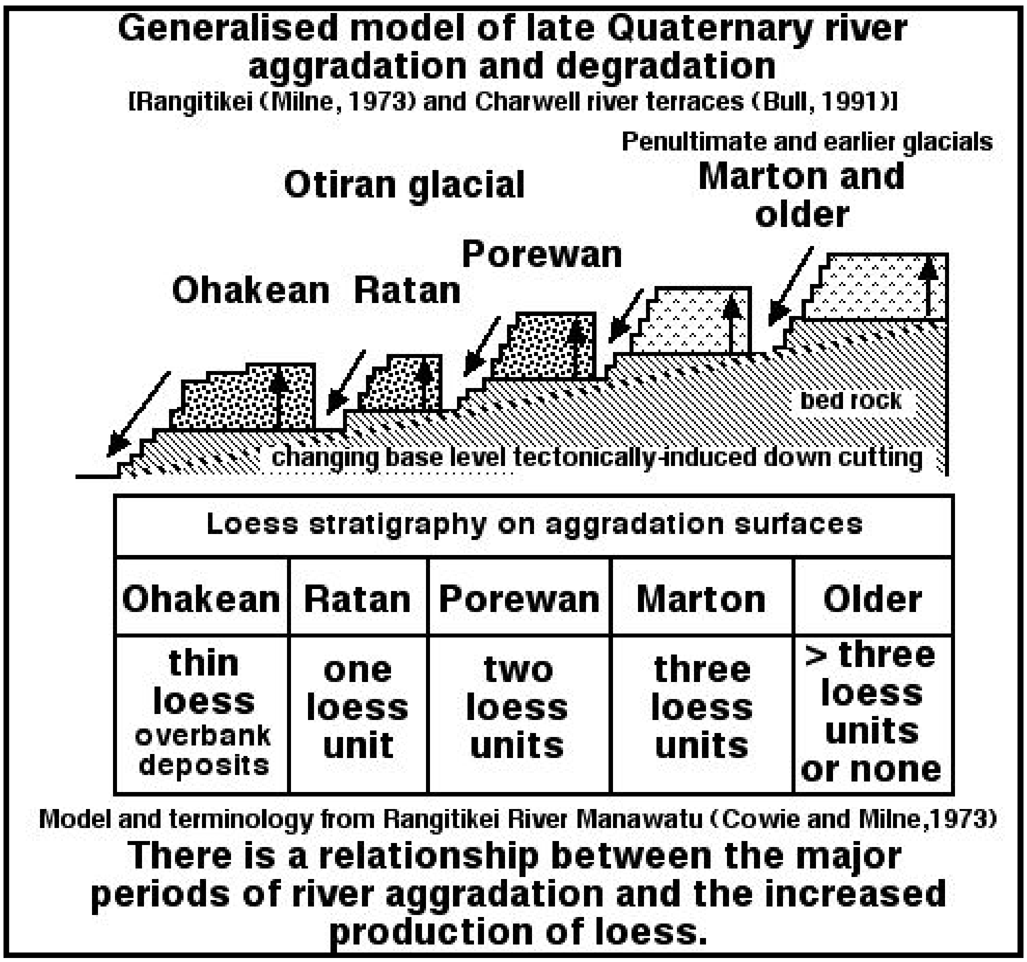

Figure 2.1Generalised model for the interaction between loess deposition (and preservation), tectonics and climatic induced river behaviour. Source P Tonkin.

Where tectonic uplift is occurring, river aggradation packages have the potential to be partially preserved chiefly on the margins of the basin. River incision will occur in uplifted area in response continued lowering of base level. Where cycles of aggradation have occurred in uplifted landscapes it is expected that that surface ages will increase with increased height above base level. In regions were loess has been preserved it has been noted that the numbers of loess sheets increases systematically with occasional exceptions on the highest surfaces. Sometimes on the highest surfaces the loess is thin or absent, either because it was never preserved on these surfaces, or an erosional event has subsequently removed it (Figure 2.1). This is particularly the case where surfaces are eroded into older bedrock units or underlain by impermeable substrates. Within the study area thin to absent loess was encountered where Kowai gravels were exposed at the surface.

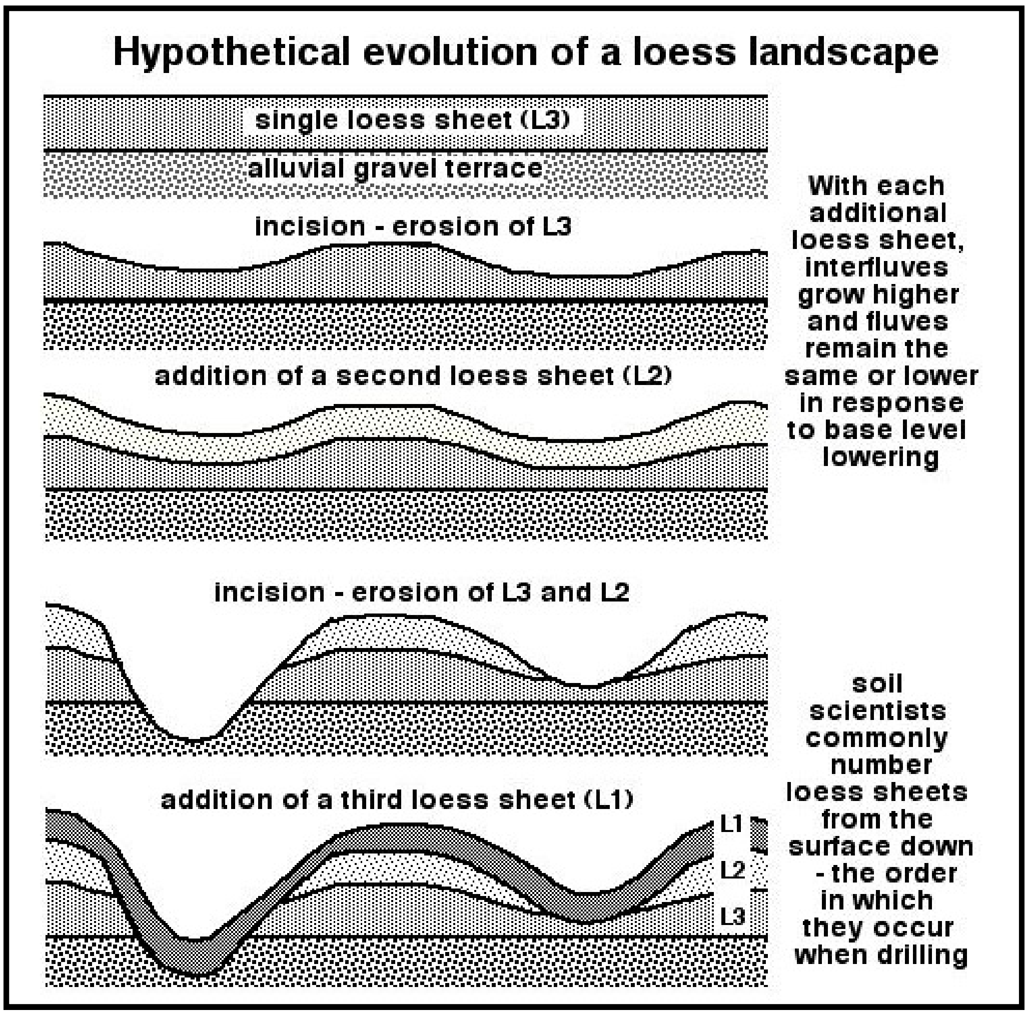

Figure 2.2Conceptual model for the development of a loess downlands topography. Source P Tonkin.

When loess is forming it mantles the topography, accumulating at rates of approximately 0.03 – 0.5 mm/yr and seldom exceeds the rate of soil formation (pers. com. P Tonkin, 2008). In the downlands of South Canterbury it has been found that the distribution of loess units can be used to infer information about how the landscape has formed through time (Figure 2.2). Here it was found that the downlands topography (rolling landscape) could be formed entirely in loess without incising into the underlying sediment. Furthermore when a number of auger holes are sunk along a transect perpendicular to the gullies formed in loess, it has been found that some of the small gullies can be relatively persistent features in the landscape suggesting that minimal erosion is likely to have occurred on the interfluvial crests of these features. In other words, the topography is generated by a relative increase in the height of the interfluves rather than by downcutting.

2.1.3 Nomenclature

For the purpose of this thesis a geomorphic surface is defined as "*a mappable landscape element formed during a discrete time period*" (Bull, 1991, page 316). As such, the mapped surfaces which are assumed to be chronologically similar are grouped together using a prefix S followed by a number which increases with inferred age (Table 2.1). It is acknowledged that S6 does not conform to the definitions above because it is chronological poorly defined.

Table 2.1Inferred surface ages and terminology for geomorphic surfaces shown on Map B (pocket).

Surface name	Distinctive feature	Inferred surface age	Surface age source
S0	Lowest surface near active channel	Modern	
S1	Soil series	<4 ka	Per com. P Tonkin
S2	Soil series	< 6 – 8 ka	Per com. P Tonkin
S2a	Marine (Para-marine) cut surface overlaid by sand dunes	<6 ka	Shulmeister & Kirk 1993 Shulmeister & Kirk 1996 Shulmeister & Kirk 1997
S3	Soil series	~12 ka	Nicol et al (1994)
S4	Single loess sheet	<30 ka	Berger et al (2001)
S4a	Fan deposits covered by "loess" alluvium	?<30 ka	
S5	Multiple loess sheets	<73 ka	Berger et al (2001)
S6	Surface at highest elevation with thin to absent loess cover	>73 ka	

The stratigraphy of the study area was briefly discussed in section 1.7.7. Wilson (1963) and Brown and Wilson's (1988) terminology for gravel formations is adopted here, mainly because it is well established in the literature. However it is apparent that the Teviotdale Formation contains a number of individual gravel packages (Nicol et al, 1994) suggesting a complex depositional history. It is also acknowledged where gravel formations overlie each other it is very difficult to distinguishing them using bore logs. As such formational names are used sparingly. Loris (2000) tabulated stratigraphic correlations for the gravel formations in the Waipara Basin and their correlatives on the Canterbury Plains.

2.2 Geomorphic surfaces

The aim of this section is to show the results of the geomorphic mapping and associated field work with particular attention to describing the identifiable features of the geomorphic surfaces, the landforms these surfaces are related to and the relationship between the geomorphic surface and the sediments with which they occur.

2.2.1 S0

S0 is identified from modern soils overlying alluvium, located near active river channels on the lower terrace surfaces. Where exposed in outcrop, the alluvium is often composed of grey cobble with finer grained material as matrix, bedded or cross bedded sand, or overbank silt and mud. Where this gravel alluvium is exposed it often overlies a brown or orange–brown gravel alluvial unit or modern swamp deposits. Sediment in the Waipara River alluvium tends to be derived from Torlesse Supergroup sandstones or reworked highly weathered Kowai gravels, commonly containing Tertiary lithologies. Tertiary clasts in the Ashley and Kowai Rivers are rarer. Thicknesses were estimated at only at a few sites but the alluvium underlying the surface tended to be to less than 2 – 10m thick.

2.2.2 S1

S1 is identified as being covered by soils aged from approximately modern to 4 ka. This surface occurs near active rivers as terrace surfaces (at higher elevations than S0 terrace surfaces) and on flood plains. On terraces this surface overlies alluvium similar to that described for S0.

From bore logs located in the Ashley River-Saltwater Creek flood plain it appears that there is an approximately triangular wedge of silty clay/ organic material overlying gravel and sand generally increasing in thickness to the North and to the Northeast (Figure 2.3). Near the Ashley River gravel and sand crops out at or near the surface

(M34/0222, M34/0223, M34/0474, M34/0574, M34/0673, M34/0802[2]), whereas wells approaching Saltwater Creek have increasing thicknesses of what drillers predominately describe as clay, silt, sand, "pug" and organics (M34/0328, M34/0566, M34/0649, M34/0359). It is likely that these sediments represent overbank and swamp deposits. Wakanui and Temuka soil types located near Saltwater Creek have been interpreted as forming in the margins of wetland type settings (Fox et al. 1964. Kear et al 1967). Saltwater Creek is located in the lowest point in this landscape and as such all the (mostly ephemeral) streams located on the downlands to the North discharge into it at time of floods. The Ashley River is currently aggrading in its lower reaches (Estrada, 2003) and is at a higher topographic elevation than Saltwater Creek.

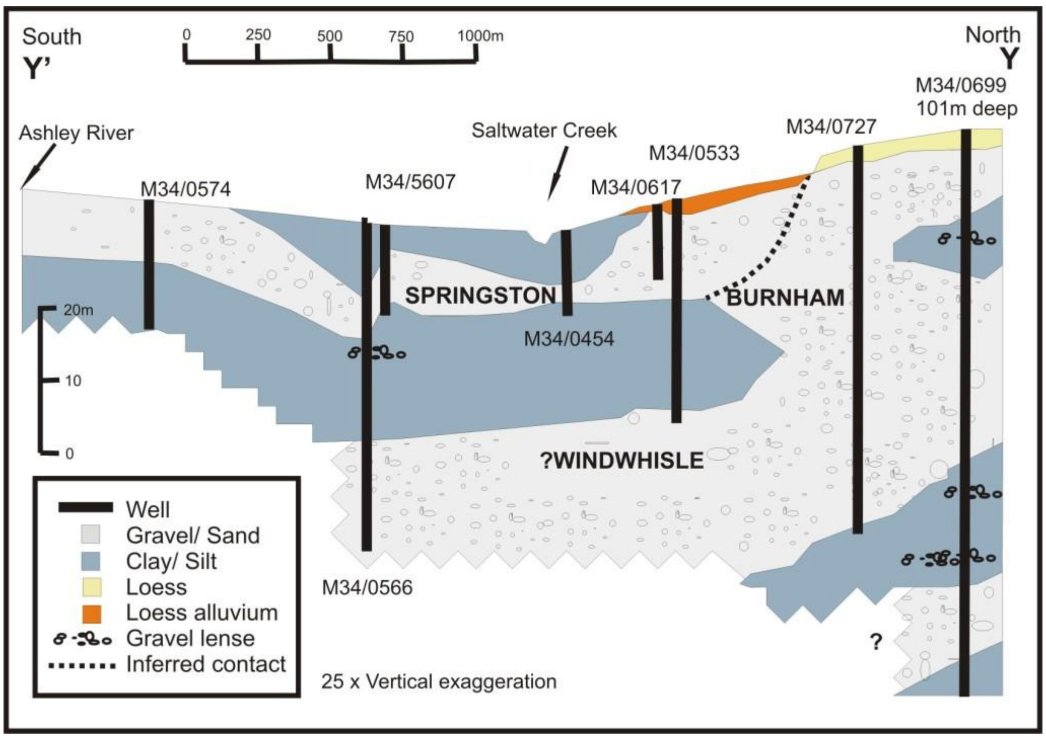

Figure 2.3 A interpretative cross section through the Saltwater Creek area. Total well depth shown except for M34/0699. Location of cross section is shown in Figure 2.23.

Deeper bores reveal alternating sequence of gravels and fine grained material (peat, clay, silt) (Figure 2.3). Using a small number of bore logs there appeared to be a "clay" layer at about -16mbgl to approximately -30mbgl (M34/566, M34/0734, M34/0703, M34/5533, M34/0611, M34/5617, M34/0184, M34/0699 and M34/5682).

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2 Bore logs can be obtained from http://www.ecan.govt.nz/wellcard/ or www.ecan.govt.nz → resource consent → consultant tools → well card.

However in individual bore logs the thickness of this layer is variable or absent (M34/0727, M34/5688 and M34/5593). In a handful of wells there is the suggestion of another “clay” layer between approximately 40 – 50mbgl (M34/0106, M34/0107, M34/0184 M34/0699 and M34/0734). Shells are only recorded in one bore log, and at a shallow depth (M34/5640, 10.9 – 15m mbgl). This bore is located 2.5 km from the coast near Saltwater Creek.

2.2.3 S2

S2 has been distinguished as being beneath soils with inferred ages from <6 – 8ka, occurring as terrace surfaces, broad low lying surfaces and on top of channel fill deposits. S2 alluvium is exposed along lower terrace surfaces near the Waipara River. The alluvium here typically consists of a thin (<2 – 3m thickness) veneer of grey cobbles with fine grained matrix. The grey gravel unit overlies orange- brown alluvial gravel (likely to be the Teviotdale Formation). Teviotdale Formation where seen in outcrop is extensive plugged up (contains significant proportion of clay/silt matrix), with clasts difficult to dislodge with a geological hammer.

Figure 2.4View of the deposits beneath S2 near the Douglas Road bridge, Kowai River (NB), Grid ref M34:843 - 866.

S2 surface occurs along the Southern margin of the Waipara Basin along the Kowai River (NB). At Grays Road bridge (gird ref M34:876 – 824) this surface is underlain by silt containing numerous pebbles, interpreted to be overbank deposits. The outcrop is several metres above the active fairway. Figure 2.4 shows deposits near the Kowai River (NB) near Broomfield. These deposits represent either buried soil or overbank deposits that have been covered by fluvial gravels, sand and mud. This surface is therefore likely to represent a period of river avulsion followed by recent downcuttting. Interestingly taken with observations at the Greys Road Bridge this indicates increasing incision by the river downstream.

Figure 2.5 Photograph of the marine cut terrace, located along Hursley Terrace Road at Grid ref N34:904 - 811. Terrace height is approximately 10m. View looking West.

Near the coast along the Kowai River, S2 occurs as channel fill deposits. These deposits are identified from contrasts in soil series on an otherwise seemingly continuous planar surface. Limited bore log data indicate that this surface is underlain by brown gravels (M34/0676, M34/0700). Along Balcairn–Amberley Rd (at M34:8548 - 7867) there is an outcrop showing the alluvium beneath this surface in which fluvial gravels, sands and remnants of loess are preserved. These channel fill deposits imply that the South branch of the Kowai River, sometime before 6 – 8 ka BP was draining to the Southeast and acting independently of the North branch. It is suggested that these palaeo-channels are related to a sea level high stand, before Pegasus Bay began prograding in the mid Holocene (Shulmeister and Kirk 1993).

Figure 2.5 shows the sediments beneath S2 near Amberley Beach. Clearly there are intercalated gravels and fine grained material (silts and muds). It is interpreted that the gravel is terrestrial and fine grained material is marine in origin and that this is a continuation of the Kaiapoi – Christchurch system. Bore logs from M34/0560 and M34/5689 show alternating clays and gravels suggesting marine incursion occurred to at least their location (though this pattern is absent in some logs, M345685). Having been depositied at sea level, these formations have since been uplifted to their present elevation.

2.2.4 S2a

S2a is covered by soils formed <6 ka. It is differentiated from S2 because the surface was formed by marine processes (Shulmeister and Kirk, 1993) and with a cover of progradational deposits marking the advancement of the shoreline seaward. The landward extent of this surface is marked by a terrace (Figure 2.5) which runs semi-parallel to the coast between the coastal hills to the North to about Saltwater Creek. This marine cut terrace is approximately 10 – 20m high near the Waipara mouth, decreasing in height steadily Southward until about Saltwater Creek where it is overlaid by coastal progradational deposits. This pattern suggests the region is being tilted up to the Northeast and emerging from South to North. Shulmeister and Kirk (1993) proposed that this terrace was formed by rivers running roughly parallel just behind beach ridges and marks the period where sea level reached its peak in the early Holocene. Sea level thereafter has been maintained at a similar level but dated beach ridge and sand dunes indicate five episodes of progradation of the shoreline (Shulmeister and Kirk, 1996, 1997) that may coincide with shoreline uplift.

The progradational deposits are composed of sand, clays and gravels. Bore logs (M34/0158, M34/5549, M34/5550) and exposures in the two sand aggregate quarries near the Waipara River mouth suggest that the progradational deposits are predominately sand, or sand-gravel mixes that appear to vary in depth from 10 – 15m.

Shulmeister and Kirk (1997) described the early – late Holocene progradational deposits as being a sand wedge; thickest in the South (6km wide) tapering off towards the Waipara mouth (<1km wide). M34/0158 shows sandy gravel overlying sand, gravel and shells on top of clay. One interpretation of this bore log could be beach deposits over shallow marine facies on marine mud. Given Shulmeister and Kirk's (1993) geomorphic interpretation this seems reasonable. Bore logs from deeper wells indicate alternating marine, marginal marine and terrestrial deposits (N34/0311, M34/0183, M34/0158).

2.2.5 S3

S3 is restricted to the Waipara Basin, to the area Lloyd (2002) referred to as the Glasnevin Plains. S3 is covered by a gravely soil thought to have formed approximately from ~12 ka ago (Nicol et al, 1994). This surface overlies a brown gravel alluvial unit which also contains occasional massive sand beds (>2m thick), silt and sand lenses (typically <1m thick). The unit crops out extensively in terraces along both sides of the Waipara River where the thickness varies from approximately 5m to >15m. The alluvial unit is thought to be equivalent to Wilson's (1963) Canterbury gravels (Figure 2.6).

Figure 2.6 View from near the Waipara River looking South at about grid ref M34:838 - 932. Clearly visible are two large gravel units (top brown unit probably equivalent to Wilson's (1963) Canterbury gravels, bottom orange–brown unit thought to be the Teviotdale Formation) The top of the sequence is overlain by a thin gray gravel unit suggesting reworking of the top of the Canterbury aggradation gravel surface. Estimated height of the terrace riser is approximately 20m high.

Bore logs from wells deeper than 50m located on this surface (n=36) reveal an interesting pattern. Wells located in the centre of the basin tend to be dominated by gravels with few fine grained layers identified (i.e. M34/0738, M34/5639, M34/5625 and M34/5707). Whereas wells along the basin margin and near the Waipara River tend to have layers of clay/ silt and rarely, peat (M34/5531, M34/5532, M34/5585, M34/5540, M34/5690 and N34/0106). This suggests that fans along the margin of the basin are contributing to the sedimentary fill and that fine grained layers are fluvially formed, either from the Waipara River or from the Waipara Downs fans or Omihi Stream (see later discussion in section 2.2.10 & section 2.2.11).

Along the Southern margin this surface abuts S2. The soils of S2 are a mix of young soils (Wakanui and Eyre inferred age of <6 – 8ka) and older soils (Pahau and Salix, inferred age of <30 ka). Black and white aerial photographs (flown 1950 and 1973) of S3 show palaeo-channels predominantly aligned Northwest–Southeast, with the boundary between S2 and S3 being marked by a clear change in appearance. The S2 surface is darker (perhaps indicating greater moisture content), with a small number of narrow distinct channels with occasional braid channels aligned Northwest–Southeast and North–South. The interpretation of these surfaces is that the S3 surface overlies a fan formed by the Waipara River. Topographic contours show that this fan is highest near the Waipara River and decreases Southward. The Kowai River (NB) flows along the margin of the Waipara fan and has been depositing sediment at this low point; occasional overtopping the channel and depositing overbank sediments (Figure 2.4). Similar interpretations have been suggested for the Selwyn and Hinds Rivers on the Plains (Anderson, 1994. Barrel et al, 1996).

2.2.6 S4

S4 is identified by the soil series that overlies it, by the characteristic rolling topographic appearance in aerial photographs, differential GPS data and lack of surface fabric, i.e. braid channels. This surface is overlaid by a single loess sheet or loess colluvium. Where exposed this surface is formed on gravelly alluvium which is interpreted to have been abandoned ~30 ka (Figure 2.7. Teviotdale (or Windwhistle Formation of the Canterbury Plains). Typically loess overlying this surface is 2 – 3m thick but is thinner or absent near channels (Appendix 2c). The loess unit can be identified in bore logs, often described as yellow or orange or brown clay (i.e. M34/0616, M34/0340, M34/0541, M34/0699 and M34/5644).

This surface has been found on the flanks of the Onepunga Anticline, Cass Anticline where it is uplifting the Teviotdale hills, on the Mound (Nicol et al, 1994) and along the margins of the Kowai Anticline (pocket Map B and Appendix 2c). The Mound along Georges Road is a remnant surface preserved due to uplift on an emerging thrust fault (Nicol et al, 1994). On the Onepunga and Cass Anticlines where this surface is mapped the loess is 1 – 2m thick (Appendix 2c). Figure 2.8 is a photograph of the gravel underlying this surface at the Teviotdale hills. The gravels contained moderately and highly weathered clasts of Torlesse suggesting Teviotdale Formation (Kowai gravel clasts are usually all highly weathered). The gravels here are dipping 25º to the Northwest. These clearly dip more steeply than the surface itself implying that the S4 surface is cut into significantly older gravels.

Figure 2.7Photograph of a single loess sheet overlying a gravel unit. Loess is 2m thick here. Photograph is of site NCOnepunga Loess 6 (reference Appendix2c), located off Cramptons Bush Road, Grid ref M34:804 - 861.

Figure 2.8Photograph of the Teviotdale Formation beneath S4, looking South, located at Grid Ref N34:909 - 899 off Stockdills Road. The grubber is 90cm tall. The dip on the gravels here is 25º, dipping towards the Northwest. S4a

S4a is identified as being beneath Okuku, Waipara, Pahau, Mayfield, Darnley, Salix or Eyre soil series and are located on fans extending from the downlands. The soils are composed of loess, loess alluvium or alluvium. It is very difficult to distinguish loess that has formed in place from loess that has been transported down a slope. Additionally, soils that formed from the same parent material can develop quite different morphologies depending on where they are located on a slope (pers. com. P Tonkin, 2008). To identify these surface cross sections (Figure 2.3), LIDAR, aerial photographs and the soil survey have been used.

The Sefton Township and surroundings area is map as S4a. There are three ephemeral streams that flow over this region so it is likely that at least a part of the deposits on these fans are modern in age. In LIDAR imagery there is a clear morphological difference between this surface and S2 and S4. S2 contains numerous incised channels and is lighter in colour, whereas S4 has smoothly rounded downlands topography and is darker in colour. S4a surface has a defined channel on a smooth convex shaped fan surface of a similar colour to that of S4. The LIDAR image also shows these fans appears to onlap onto S2, with channels on S2 being diverted around the S4a edge. S4a is at a lower altitude that the S4. It is interpreted that these surfaces represent loess colluvium moved down slope so that strictly the relative timing of the formation of this surface is younger than the formation of S4 and may be diachronous and possibly still actively forming (Figure 2.3).

S4a forms an apron around the Teviotdale hills suggesting it is a fan deposit. Bore logs from wells 50m or deeper show gravels and fine grained layers (M34/0772, M34/5603, M34/5606, M34/5642 and M34/5684). This pattern is interpreted to represent fan deposition from the small ephemeral streams that flow from the Teviotdale hills. The soils overlying these fans are highly mottled suggesting high water content. A significant proportion of this surface was mapped by Loris (2000) and Lloyd (2002) as (now drained) wetlands.

S4a has been mapped along the Northern side of the Kowai Anticline. Here there are numerous fans extending from the hills to the South. Inspection of a gully within one of these fans (at grid ref M34:793 – 853) showed only recent alluvium exposed. However there are a number of inset terraces related to this fan which suggests continued lowering of the base level. The soils nearby are Okuku and Waipara series which suggest that part of this landscape may be blanketed by loess or reworked loess.

2.2.7 S5

S5 is defined by two or more loess sheets and has been identified from soil series that cover the surface, LIDAR imagery, aerial photographs and the soil survey. In LIDAR and aerial photographs this surface appears highly dissected and occurring at higher altitudes than S4. The soil survey confirmed that these areas had >3m thickness of loess or contained at least two identifiable loess sheets (Figure 2.9, Appendix 2b).

There are only a small number of wells that penetrate through this surface, and only a few with reliable bore logs. All these bores are located on the surfaces South of Amberley. M34/5609 (85m deep) shows gravels and silts until about 50 mbgl, below this depth there are clays, sands, organics and gravels. The organics layer is within a fining upwards sequence (gravel, organics & clay, sand then clay (?mud)) which is interpreted to represent terrestrial through marginal marine to marine environments. M34/0108 (118m deep, located at 149 masl) and M34/0148 (88m deep, located at 114 masl) both have a peat layer overlying blue clays & blue gravels at about 69 masl and 31 masl respectively and both have numerous gravel and clays layers showing through out their length. Neither bore logs show a fining up sequence associated with the peat layer. It is therefore interpreted that these bore logs indicate fluvial deposition with occasional slack water and alluvial fan deposits. M34/0016 (70m deep) and M34/0147 (85m deep) bore logs shows thin layers of clays, sand and gravels. This sequence is similar to what would be expected in a small alluvial fan system.

Figure 2.9Photograph of loess exposed in a Road cutting along Balcairn Amberley Road. The Road cutting is 3.7m tall, with additional 0.8m of loess encountered when drilled, with a total thickness of 4.5m. Note the A horizon is absent suggesting some of the profile has been removed. NC Balcairn Loess 6, grid ref M34:853 – 819.

2.2.8 S6

S6 is identified by a thin soil or thin loess sheet (<1m) overlying country rock at a higher altitude than S5. In aerial photographs and LIDAR this surface is highly dissected. This surface likely represents a grouping of a number of surfaces of different ages that are indistinguishable due to the amount of modification that has occurred since their formation.

Figure 2.10 Photograph of a road cutting along Onepunga Road showing loess overlying Berrydale Greensand (Andrews, 1963). The dashed line is an inferred contact. Located at grid ref M34:782 – 882. Road cutting height is approximately 3m.

There is only one well that the author is aware of that penetrated through this surface, Kowai–1 (Hoolihan, 1978). This bore encountered Kowai Formation near the surface and to a depth of 450m but with marked discordance in dips suggesting intersection with a fault at depth The Kowai formation is thoroughly discussed by Browne and Field (1985). Exposure of this surface and underlying geology occur on the Teviotdale hills, along the Southern side of the Onepunga Anticline, in the middle of the Waipara gorge and in the upper catchment of the Kowai River (NB & SB). For the most part these exposures show this is primarily an erosion surface underlain by Kowai formation (Appendix 2c). A road cutting along Onepunga Road however reveals that this surface transects other lithologies being underlain by Oligocene Berrydale Greensand (Figure 2.10, Andrews, 1963). The location of this section is problematic in that it occurs to the South of Onepunga Anticline (and outcrops of

Kowai formation) whereas according to the geological map (Map A pocket) sediments should be young to the South of that feature.

2.2.9 Waipara Downs fan system

The Waipara Downs fan system is located to the North of the Waipara River and East of the Waipara Township (Figure 2.11). This region contains the Weka fan (Nicol et al. 1994) which has a surface of equivalent age to the S3. Located along the shoulders of the Weka fan are smaller alluvial fans that are currently active. The last aggradation event of these smaller alluvial fans occurred in the 1950's when floods carried sediment down small streams where it was depositing on the gentler slopes of the fan surface (per com. P Tonkin 2008). In the worst affected areas fence posts were buried by sediment, prompting the formation of the Glenmark soil conservation district. A single loess sheet occurs at the surface near the Waipara River but is buried by recent alluvial sediment Northwards towards the Weka fan.

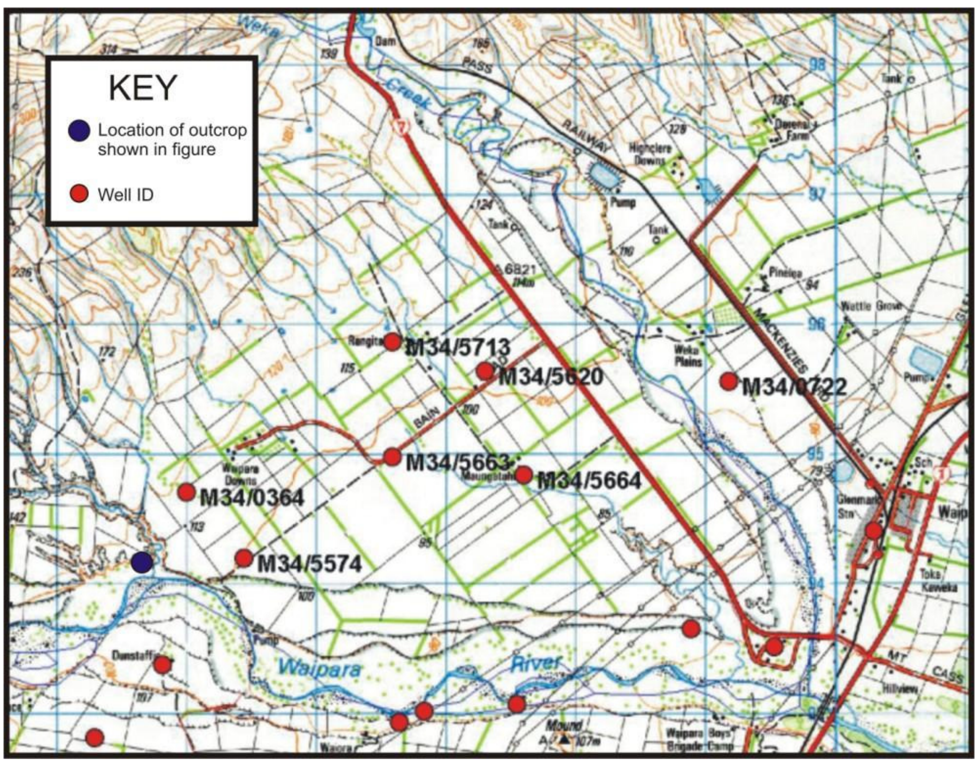

Figure 2.11 Map showing the locations of 50m+ deep wells with bore logs located on the Waipara Downs fan. Also shown is the location where Figure 2.12 was taken from (blue dot). Grid squares are spaced kilometre apart.

Figure 2.12 is a photograph of the sediments beneath these surfaces. There are several layers of gravel and fine grained material. The gravel is fluvially derived and likely to have been formed by the Waipara River, whereas the fine grained material (silts and muds) are interpreted to be alluvial fan deposits. The gravel layers can be seen to thin to the North (Appendix 2c). These deposits are relatively persistent in lateral extent and can be viewed along the Waipara River between M34:840 – 942 & M34:850 – 941, and large gullies to the North. Bore logs from 50m+ deep wells show that interbedded gravels and clays continue Northwards till M34/0364, M34/0722, and M34/5564 and M34/5713 but clay layers are largely absent in the log of M34/5620 (Figure 2.11). There are few other wells in this region partly due to the Glenmark irrigation scheme (surface water scheme sourced from the Weka Creek).

Figure 2.12 Photograph of the Weka fan, taken from the level of the Waipara River at grid ref M34:848 - 942. Terrace riser is approximately 15 – 20m high. Shown in the photograph are alternating gravel and fine grained deposits. The gravels are thought to be deposited by the Waipara River while the fine grained deposits are thought to be deposited by the Weka fan.

2.2.10 Omihi valley

The Omihi valley extends into the Northern part of the Waipara Basin. The geometry has been defined from seismic surveys conducted by Finnemore (2004). Generally Finnemore (2004) showed that the Omihi valley Quaternary basin fill is broadly synclinal shaped, increasing in thickness to the North. Near the confluence with the Waipara River the Quaternary basin fill is wedge shaped in response to the uplift on the Omihi fault zone. In this region aerial photographs show palaeo-channels preserved on the surface which indicate stream flow from Northwest to the Southeast, towards the low point in the landscape. On both sides of the valley fans have built out although generally the fans on the Eastern side are larger. These fan deposits were interpreted by Finnemore (2004) to be found to depths of about 100mbgl along the Western margin, which are then underlain by fluvial deposits. Finnemore (2004) hypothesized that the Omihi Stream has been largely confined to the Western side of the valley due to tectonic uplift to the East and the building out of these large fans. The modern river now flows obliquely across to the Eastern side as it approaches the confluence with the Waipara River and locally exposes the strands of the Omihi Fault (Nicol et al 1994).

Harris (1982) described the Quaternary sediments that occurred near the Omihi Stream in the lower half of it reach. Near the confluence of the Waipara River and Omihi Stream Harris (1982) described two wedges of gravel that tapered out to the North, intercalated with silts, sands and muds. It is interpreted that these deposits are similar to that shown in Figure 2.12 and represent Waipara River fan material interbedded with Omihi Stream fluvial deposits. Harris (1982) showed that the Omihi Stream has, through recent geological time been a meandering system, typically low energy, depositing predominantly sand and finer sediment. This may be because it is controlled by aggradation in the Waipara River, where onset of Holocene downcutting into the present channel may be as recent as 2 ka years ago. Harris (1982) also described the deposits of fans emanating from the hills to the East interbedded with fluvially derived material.

Bore logs from wells 50m+ in depth (n=24) show that clayey silt, sand and gravel occur throughout with no obvious trend evident. However J Weeber (pers. com., 2008) using bore logs discovered a seemingly continuous clay and peat layer near the confluence of the Waipara River and Omihi Stream. He interpreted this layer to be a lake deposit. P Tonkin (per com. 2008) when investigating a road cut in the lower Omihi catchment found layers he interpreted to be lake deposits. He interpreted these deposits to be formed when the Waipara River fan impounded the discharge from the Omihi Stream. This could happen when the growth of the Waipara River fan exceeds that of the Omihi Stream fan. Uplift of the Black Anticline across the exit of the Waipara River into the lower Waipara Gorge may also create ponding and restricted flow in this area. Uplifted fan deposits in a cutting on the nearby Mt Cass road are indicative of former low flow distal deposition into swamp deposits (Appendix 2c).

2.3 Seismic reflection surveys

Three seismic reflection surveys were conducted in the Waipara Basin for this project. The seismic lines are referred to as Line 1 through 3. Line 1 and 2 aimed to image a fault in the Southern Waipara Basin near Amberley. This structure was discussed by Loris (2000). A part of this fault has recently been classified as an active structure on the latest GNS Q Map (per com. J Campbell. 2008). For this project the fault is informally called the Broomfield Fault, named after the nearest locality. The Broomfield Fault is recognised by a scarp aligned across the Waipara Basin with the Amberley Swamp impounded behind it on the Northern side (Figure 2.13), indicating upthrow on the Southern side of the fault. The scarp dies out before the Kowai River (NB) but the inferred continuation of the fault is coincidental with the Northern edge of a hill on the opposite side of the basin. The Northern edge of the hill is relatively straight and steep, and leads naturally to an intersection with the unnamed Kowai Anticline Fault.

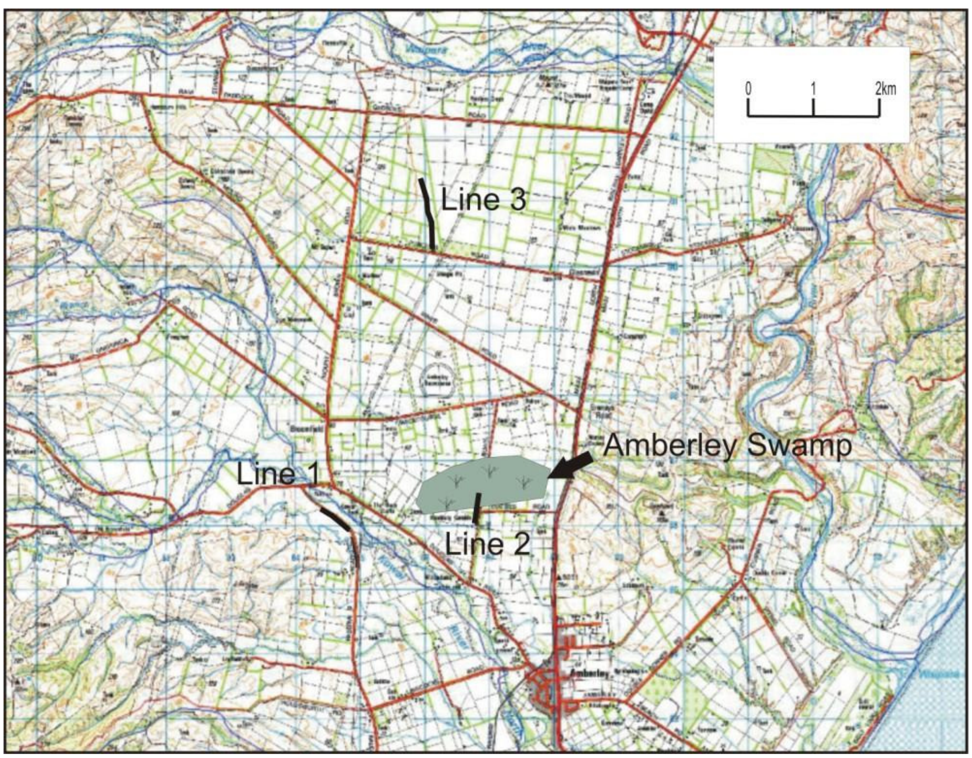

Figure 2.13 Map showing the locations of the three seismic surveys conducted for this project. For discussion on the Amberley Swamp see section 3.2.4.

Line 3 aimed to image the gross structure of the basin fill sediments. Shown on the geological map in Loris (2000) there is a small inferred fault oriented generally East West located on the Northern side of the Kowai Anticline, which has been drawn protruding into the basin proper. The second aim of the survey was to image this fault. The locations of the surveys are shown in Figure 2.13.

The seismic survey was conducted by the author (assisted by a small, but dedicated crew) using the of University of Canterbury Department of Geological Sciences' seismic equipment. The survey was conducted with hammer and plate as a source, using geophones spaced 5m apart and shot points 10m apart. Seismic theory, methodology and process flow are presented in Appendix 2d.

The interpretations of these seismic profiles are based on minimal ground truth, i.e. a small number of bore logs where available. In addition these interpretations assume that the stratigraphic correlations of Wilson (1963) are correct, that erosion has not removed entire formations, that the wavy/hummocky reflectors represent fluvial deposits, that the geomorphic interpretations are sound and that strong reflectors represent contacts between formations.

2.3.1 Line 3

Shown in Figure 2.14 is the entire record obtained from line 3. There are no data in the upper 20 – 25m of the profile. Reflectors are present to about 340m depth at 100 - 200m distance. The irregular depths to the strong reflectors indicated that there are no multiples in this profile (per com. M Finnemore, 2009). Furthermore the apparent dips of these strong reflectors increase incrementally with depth, from 0 – 2º to 5 – 6º.

At the top of the section there is a strong reflector at 40 – 50m depth. The apparent dip of this reflector is 2º to the North. Above and to the North of this reflector there is a discordant package of wavy and discontinuous reflectors extending to a depth of 160m in the Northern part of the profile. Similar locally dicordant hummocky reflectors are present in the Southern section in a concave trough extending to approximately 120 m. Under the hummocky package there is a strong reflector with an apparent dip of 1 – 2º to the South. This reflector extends from 0 – 500m distance but is not traceable Northwards from about that point. There are three strong reflector packages from 200 – 300m depth in the Southern half of the profile. They are continuous across the profile, though less well defined in the Northern section. The apparent dips of these reflectors are, from top to bottom, 3 – 5º, 4 – 5º and 5 – 6º.

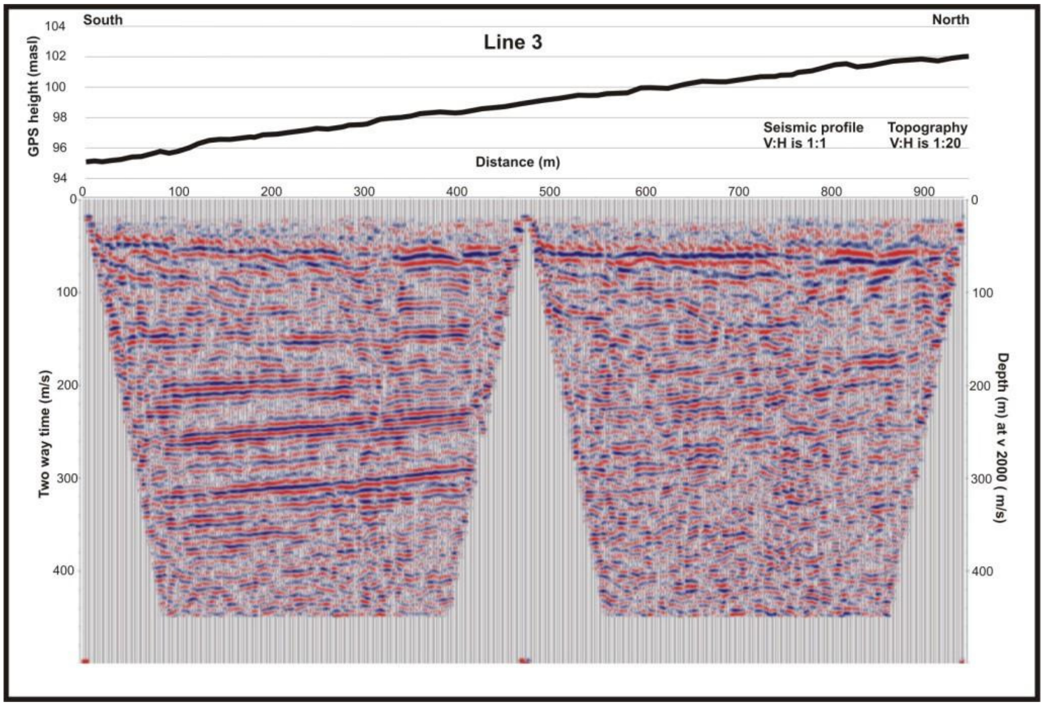

Figure 2.14 Seismic profile from Line 3. Note right hand vertical axis, v = velocity. Above the seismic profile is the surface topography as determined from differential corrected GPS.

There are a number of deeper bores with logs near the line. Those to the East of the line record predominantly gravels (M34/0765, 102m deep, 750m away from the closest point to the line, to the Northeast, M34/5625, 94m deep, 850m East, M35/5629, 132m deep, 230m Southeast, M34/5623, 126m deep, 500m Southeast). To the West of the line well logs are dominated by gravels, but contain meter scale beds of silt and clay (section 2.2.5).

It is interpreted that the top strong reflector at 40 – 50m depth represents the top of the Teviotdale Formation. This implies that the Canterbury gravels thin towards the South (section 2.2.5). The base of Teviotdale Formation is interpreted to be 100m in the South and approximately 180m in the North. The hummocky reflectors in the North may represent a series of buried channels and an erosional contact into the underlying formation. This relates well to the projected geometry of the terrace of Teviotdale gravels incised into the North flank of the Onepunga Anticline projected down plunge into this section line. The three strong reflectors beneath the Teviotdale Formation are interpreted to be part of the Kowai formation which is also what would be expected by projecting the underlying geology at the nose of the Anticline This is primarily based on the thickness of this formation which is likely to be several hundred meters (Hoolihan, 1978. Browne and Field, 1985). These reflectors may represent the transition from marine to terrestrial where there are numerous alternations of shell beds with bluff forming thick gravel units (Figure 2.15 and Figure 2.16). This formation is known also to contain decimetre - meter mudstone beds (Browne and Field, 1985).

Figure 2.15 Photograph of the marine portion of the Kowai formation, Onepunga Road, Upper catchment Kowai River (NB). Looking North towards the Onepunga Anticline. Seen here meter scale beds of sandstone, gravels and shells beds, some packages forming extensive bluff forming units likely to produce good reflectors Grid ref M34: 773 – 896.

An alternative explanation may be that here the Pliocene – Pleistocene formations are thin and the lower reflectors represent limestone members of Mount Brown Formation. However this would require a considerable amount of erosion to take place. The preferred interpretation for this seismic profile is that the Kowai formation is found at a depth of 180m onwards. No fault was detected in this seismic profile.

Figure 2.16 Photograph of the shell beds within the Kowai gravels. The photograph was taken on the Teviotdale hills, at grid ref N34:905 – 887. Thinner and more lensoid bedding is unlikely to produce strong, continuous reflectors.

2.3.2 Line 2

Shown in Figure 2.17 is the seismic profile obtained from line 2. There are no data above 20 – 30m but reflectors present to the bottom of the image are regarded as real and contain no multiples or refractions.

There are strong horizontal reflectors to 45m depth, which are near continuous from 115 – 480m distance and are hummocky to wavy. Below these reflectors, between 200 – 400m distance and between the depth of 50 – 150m, there is a set of strong reflectors that dips[3] at 23º to the North. There is a distinct fold to this set of reflectors at about 325m distance. Above and below this reflector, between 175 – 480m distance, there are a series of more irregular, spaced, moderately-strong reflectors that dip to the North at 23 – 25º. The dip does not appear to increase with depth. Some of these reflectors are also convexly shaped in places and show smaller wave length folds and discontinuities towards the down dip end. These reflectors become chaotic and displaced at 115 – 225m distance with the boundary between the regular and

[3] The seismic profile is approximately orthogonal to the fault scarp.

chaotic zone dipping to the South and projecting to the surface near the base of the surface scarp. At 0 – 115m distance, to the South of the chaotic zone there are weak reflectors that are concave to horizontal. In places in the interface between the upper horizontal package and the dipping set there are weaker reflectors occupying concave irregularities in the top surface of the dipping package.

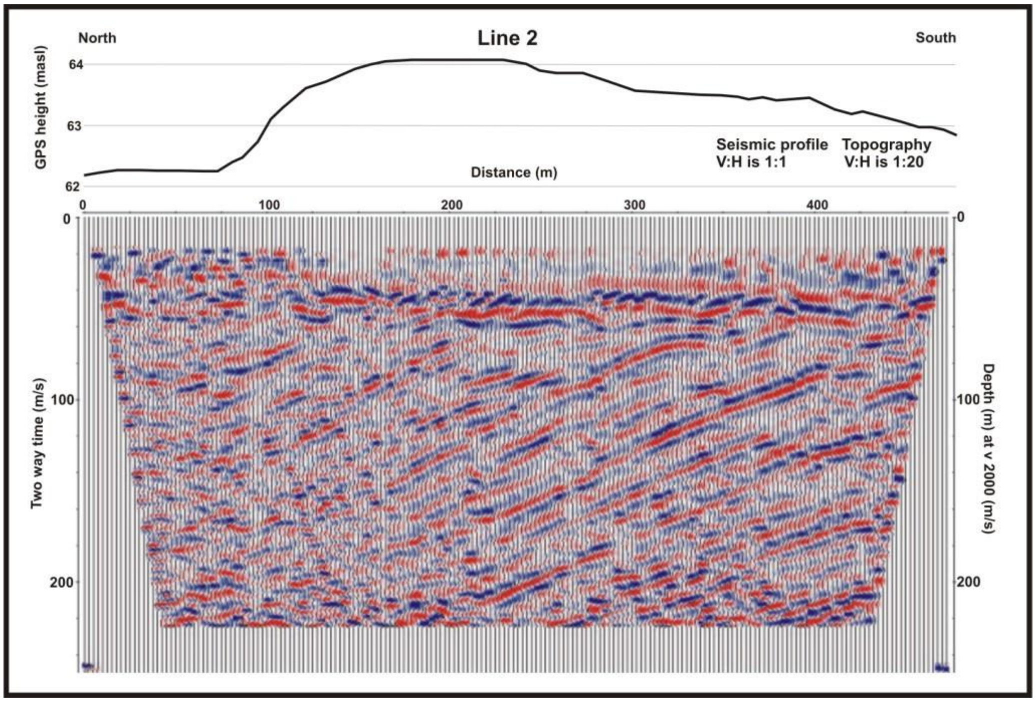

Figure 2.17 Seismic profile from Line 2. Note right hand vertical axis, v = velocity. Above the seismic profile is the surface topography as determined from differential corrected GPS.

There are limited wells in the area with bore logs, only one that penetrates to 200m (M34/5707) and no wells with bore logs within the Amberley Swamp. M34/0758 (48m deep, 600m East of line 2, on the upthrown side) bore logs consists of brown gravels & silts overlying blue gravels and silts. M34/0745 (36m deep, 650m to the Northwest on the downthrown side) bore logs record gravels with a thin papa layer at depth. M34/5707 (208m total depth[4], 1450m ~North on the downthrown side) shows gravels throughout its length. Generally all the logs show irregularly spaced meter to tens of meters scale bedding of gravels with limited clayey- silts. Within the swamp it is expected that there is a sequence of fine grained slack water deposits, with occasional gravel inclusions.

[4] Screened at 120 – 130 and 138 – 146 mbgl. Well depth states 146m, bore logged to 208m. Properly drilled to depth then pulled back and screened.

The gradation into chaotic reflectors at 115 – 225m is interpreted to represent a shear zone. There is no single obvious fault; rather it appears that there are numerous discontinuities within a disturbed zone. A fault interpretation for this feature is supported by clear offsets of reflectors, clear folding, the topography and the presence of the Amberley Swamp on the down thrown side. Reflectors to the North of the fault zone are inclined horizontally to slightly Southwards dipping which likely represents a syncline forming on the downthrown side. At 375 – 425m distance and at 200m depth reflectors are offset, suggesting faulting. The obvious folds suggest that further deformation is occurring to the South of the image. It was noted during the reconnaissance stage of the seismic survey that the surface to the South of the Amberley Swamp was crinkled, though this may be palaeo-channels from the nearby Kowai River (NB).

It is interpreted that the moderate to strong reflectors seen on the South margin of Figure 2.17 is the Kowai Formation (see previous section). This interpretation is preferred due to the relatively close spacing of the reflectors and the number of reflectors present. Alternatively it may represent compression of Quaternary formations above a growing shear zone and/or it may represent Tertiary sediments exposed by erosion. However it would be expected if syndepositional faulting was occurring that the dip would increase with depth. The constant dip of the Kowai Formation with depth implies post-depositional faulting. The reflectors to the North of the shear zone are likely to represent swamp deposits and alluvium from the uplifted fault scarp.

2.3.3 Line 1

The full seismic profile is shown in Figure 2.18. Above about 30m depth there are no data as these were removed during processing (swamped by seismic refractions). There are reflectors in this profile down to a depth of 280m depth. Data in the right corner (below distances 425 – 480m) are generally of a poor quality which is likely to be caused by difficulties in planting the geophones (here there was limited space on the road verge).

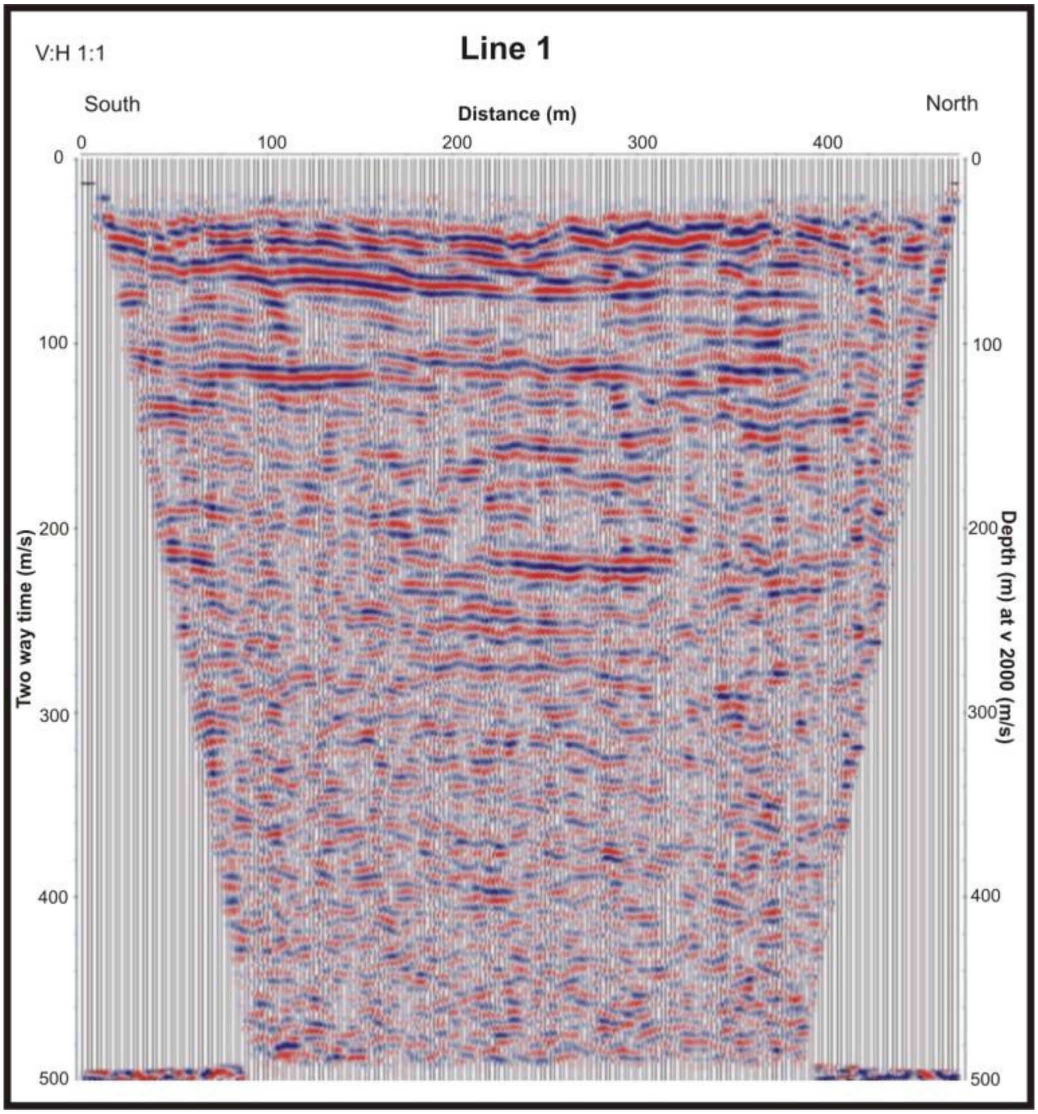

Figure 2.18 Seismic profile from Line 1. Note right hand vertical axis, v = velocity.

Above 70m depth there is a package of strong reflectors. These reflectors are orientated generally parallel to sub-parallel the ground surface with most reflectors being near continuous across the profile. Individual reflectors when traced are wavy. From 70 – 110m depth there are infrequent weak reflectors, which appear to be generally flat lying. At about 110m depth there is a thick band of strong horizontal reflectors. Some of these reflectors are traceable across much of the profile. These reflectors are slightly wavy but have less curvature than the reflectors at 30 – 70m depth. From about 125 – 220m there is a package of generally infrequent weak reflectors, though from 140m – 160m depth there are sets of relatively strong reflectors between 200 – 480m along the horizontal axis. These packages of reflectors are generally lying sub parallel to the ground surface. The reflectors when traced are relatively wavy. At 220m depth, located centrally, is a set of relatively strong reflectors. These reflectors have an apparent dip of 2º to the Northwest but appear to tilt up near the end of the profile Below 220m to about 280m depth there a package of reflector located centrally within the image. In the lower 200 m of the section discontinuous wavy reflectors give the impression of a general low dip to the Northwest.

It is interpreted that the reflectors at 30 – 70m depth are fluvial gravels. This interpretation is based on the hummocky appearance and supported by bore log data from M34/5532 (51m deep) which is located approximately 300m to the Northeast of the line 1. The bore log from this well records predominately gravels and sands ± clay and silt. These deposits are though to represent <12 ka deposits. The thickness of this package is 70 - 80m which is much greater than is observed in outcrops. The thickness of these gravels is attributed to its proximately to the Kowai River (NB). This interpretation is supported by geomorphic interpretations which suggest the Kowai River (NB) has drained through this outlet towards Amberley since 12 ka (section 2.4.5). It is interpreted that these modern sediments are underlain by the Canterbury formation to 115m depth. From 115m to 210m depth is interpreted to be Teviotdale Formation, with the lowest strong reflector at 210m depth being interpreted as the top of the Kowai formation. At approximately 400m distance there is warping and displacement along two small faults. The faults penetrate to the top of the profile (30m depth). These faults may be back thrusts possible from a larger fault zone.

2.4 Morphometric analysis

2.4.1 Stream gradient index and stream profiles

Hack's (1973) stream gradient index has been used extensively in North Canterbury to indicate the presence of active structures (Yousif, 1987. Litchfield, 1995. Estrada, 2003. Litchfield et al. 2003). Changes in stream longitudinal profiles can be altered by climate, sediment load, changes in stream flow (i.e. downstream from the confluence of streams, major springs), changes in lithology and tectonics (Litchfield et al. 2003). If the first four factors can be accounted for, then it is assumed the anomaly in the stream longitudinal is tectonically induced.

Hack's (1973) stream gradient index assumes that a stream at grade will assume a logarithmic form, and is a ratio between a portion of the gradient of a stream longitudinal profile (GI) against the gradient for the entire length (K) where (Figure 2.19);

$$GI = \Delta H / \log_e L_2 - \log_e L_1 \qquad K = H_i - H_j / \log_e L_j - \log_e L_i$$

Where H is elevation and L is length. For a stream with a concave longitudinal profile the GI/K ratio should increase from less than one for segments close to the divide to slightly greater than one near the end of the profile (Litchfield et al. 2003). Anomalies are recognised where GI/K values are significantly different from one. It is assumed that climate affects all streams approximately equally and simultaneously.

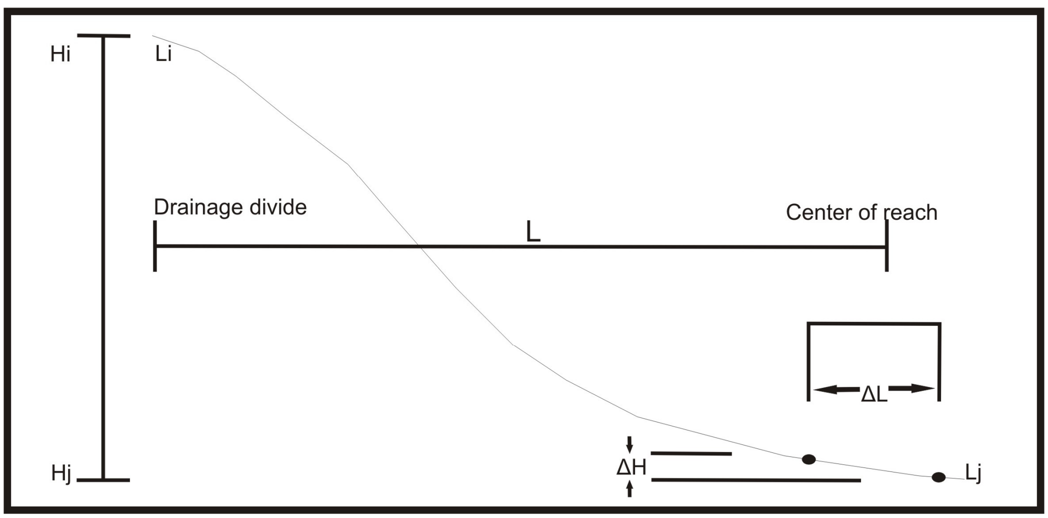

Figure 2.19Idealised longitudinal stream profile showing the terminology used in the stream gradient index analysis. Adapted from Hack (1973).

Stream gradient index analysis was performed on 25 streams and rivers in the Kowai zone (Appendix 2e, Figure 2.20 and Figure 2.21). Figure 2.20 shows profiles from Number One and Two Creeks. Number Two Creek flows down the Eastern side of Mount Grey across a number of mapped faults (Cowan, 1992). The stream gradient analysis showed anomalies at these locations. Two further anomalies were located on the profile; the second (3.70 in Figure 2.20) is though to be the lithological contact between Torlesse Supergroup and Quaternary formations, the first is though to be an unrecognised fault associated with the Mount Grey fault zone.

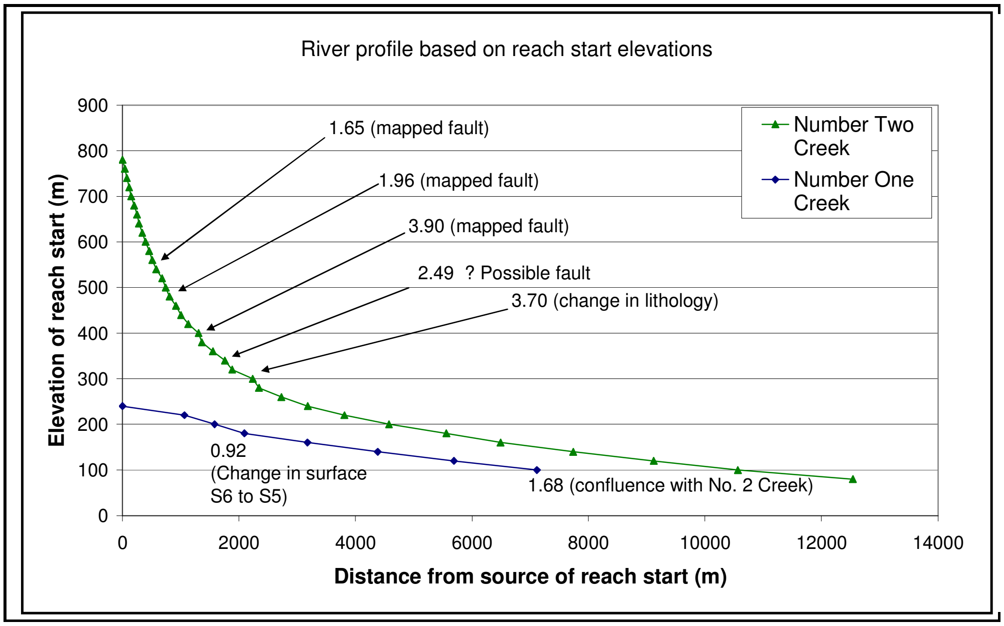

Figure 2.20 Stream longitudinal profiles of Number One and Two Creeks plotted arithmetically on both axes with an approximate vertical exaggeration of 8. Figures are results from the Stream gradient index analysis where horizontal distance is logarithmic. The faults were mapped by Cowan (1992).

Number One Creek is a smaller spring fed stream which starts flowing within the Quaternary units. The first anomaly is related to a change in surface, going from S6 to S5. These two surfaces are clearly identifiable in the longitudinal profile shown in Figure 2.20. The second anomaly relates to the confluence of this stream with the Number Two Creek.

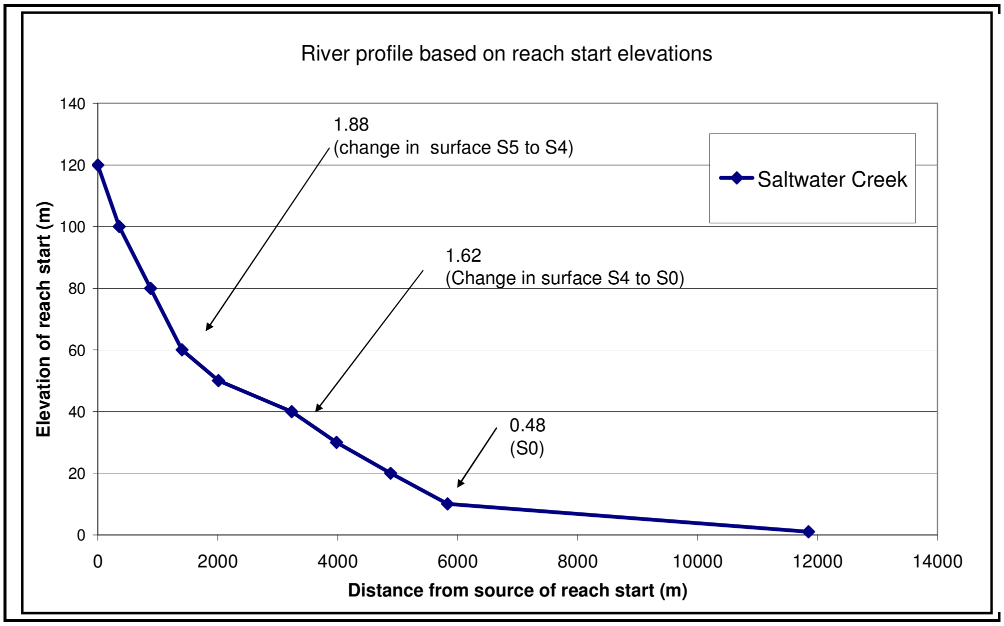

Figure 2.21Stream longitudinal profile of Saltwater Creek plotted arithmetically on both axes with an approximate vertical exaggeration of 50. Figures are results from the Stream gradient index analysis.

Figure 2.21 shows a typical profile for a stream flowing over the downlands (Appendix 2e). It is evident in Figure 2.21 that this landscape is stepped. The positions of these steps are coincidental with the surfaces mapped here. It is therefore interpreted that the stream gradient index values are indicating the presence of slopes and planar surfaces, where the slopes have values >1 and the planar surfaces have values <1. This technique has consequently been used to validate the boundaries between surfaces. The migration of knick points has not occurred here.

There were a small number of anomalies picked up by the analysis that could not be attributed to any other factor and therefore are assumed to be tectonic in origin (Depicted with A in Figure 2.23). The first set of anomalies are identified across three streams near Amberley. It is interpreted that these features are an extension of the fault system uplifting the Anticline to the North. The second set of anomalies was seen in three stream profiles near the Ashley Township. These are interpreted to be extensions of the Loburn and Ashley faults mapped by Sisson (1999). The Northern most inferred fault is obvious in LIDAR imagery, while the location of the Southern fault is marked by a small terrace.

2.4.2 Drainage patterns

The channels of the major streams in the upper catchment of the North Branch of the Kowai River show a similar morphology in that they are all actively incising into their Northern banks exposing sediments beneath older surfaces and frequently have younger surfaces preserved on their Southern banks. Holbrook and Schumm (1999) attributed similar patterns to lateral tilting.

Figure 2.23 and Map A shows that this upper catchment of the Kowai River is flanked by two tectonic features; to the North the Bobby's Creek fault and associated Onepunga Anticline, (Nicol, 1991. Nicol and Campbell, 2001. Campbell et al, 2003) with the Kowai Anticline to the South (Hoolihan, 1978. Katz, 1982). It has been noted by numerous authors that folds in this part of North Canterbury are asymmetrical hanging wall Anticlines (Yousif, 1987. Nicol, 1991. Cowan, 1992. Barnes, 1993. Pettinga et al, 2001) with steeply dipping faulted limbs and shallower dipping opposing limbs. Duffy (2008) noted that the syncline associated with the East-West striking Bobby's Creek fault had been almost completely overridden by the associated Anticline. To fit the observed geometry displayed by the streams in this upper catchment of the Kowai River the Southern limb of the Onepunga Anticline would need to be tilted to the North by the Kowai Anticline. This implies greater activity on this fault system than has been previously been recognised. This observation is supported by the gradients and elevations reached by the older surfaces S5 and S6 surfaces on the seaward flank along the Kowai zone.

2.4.3 Air gaps

The upper catchment of the Kowai River (NB) is flanked to the North by the Onepunga Anticline (Map two, pocket). Tertiary sediments have been uplifted and dip to the Southeast. Near Mount Grey, cut into the uplifting Tertiary sediments are two half circular erosional features (Figure 2.22). These erosional features are at a similar elevation to S6. It is interpreted that these features are air gaps cut into the uplifting structure by a major River system, most likely the Waipara River. This suggests that the Waipara River at some point was draining through this valley towards the Southeast.

Figure 2.22 Photograph of the two air gaps cut into the Onepunga Anticline. Photograph is taken along Onepunga Road, on S6, facing the Northwest. Kowai River (NB) flows in the valley in the middle of the photograph.

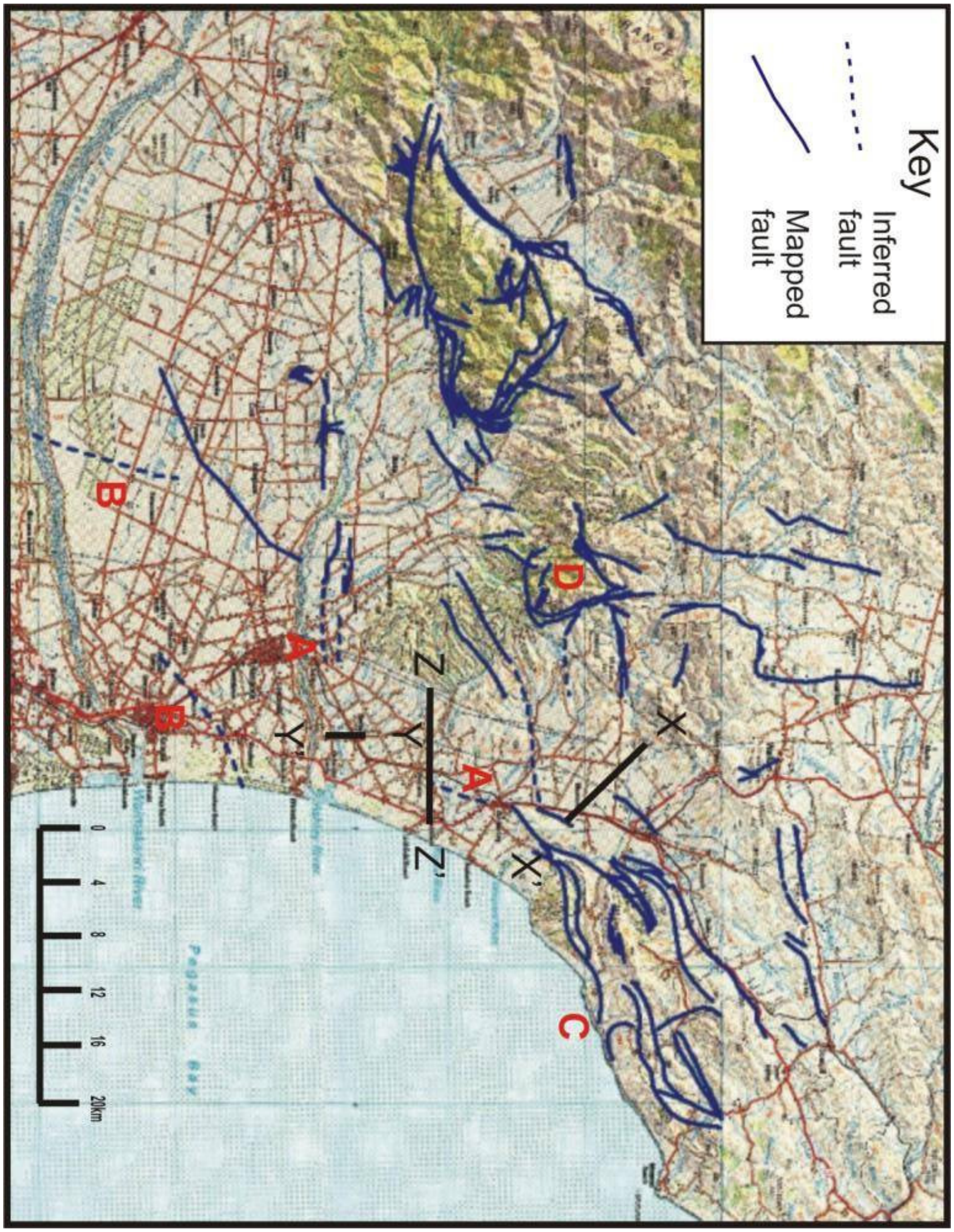

Figure 2.23 Map showing the location of known onshore active faults in and near the study area. Note Barnes (1993) mapped numerous faults offshore North Canterbury. A is used to show the locations of faults inferred from stream gradient index analysis from this study, B for faults inferred from Estrada (2003) using the same technique, C are faults mapped by Yousif (1987) using the stream gradient index method and aerial photographic mapping, D are faults mapped by Cowan (1992). X & X', Y & Y' and Z & Z' are the approximate location of the cross sections shown in Figure 2.3, Figure 2.24 and Figure 2.25.

2.5 Landscape development

2.5.1 Kowai zone

A simplified interpretative lithofacies cross section of the sedimentary structure of the Kowai zone is shown in Figure 2.24. It should be noted that this figure was constructed using a very small number of wells, with no suitable well in the middle section. The construction of the simplified cross sections required the projection of wells onto an arbitrary datum, with wells considered suitable if they were within 500m of the datum.

It is proposed that the sediments within Kowai zone have formed in response to changes in climate and influenced by tectonic uplift. During periods of low sea level, rivers flow to a lower base level and deposit material on the newly exposed continental shelf. Barnes (1995) described sediments offshore North Canterbury that he interpreted as the isolated remnants of fluvial sediments. Offshore in Mid Canterbury Browne and Naish (2003) recognised wedges of sediment onlapping onto the continental slope, interpreted to be deltaic sediments. When sea level rises, marine waters advance onto land with potential for marginal marine and marine deposits to form. Barnes (1995) found that these deposits (high stand system tracts) were readily preserved. During periods of quiescence or when sea level peaks, cliffs can be formed by the sea (Shulmeister & Kirk 1993) which erodes landward as happened in the early Holocene.

In the Kowai zone loess mantled geomorphic surfaces help constrain the extent of the marine during the late Quaternary. A soil transect across flight terraces on the Northern banks of the Kowai River (SB) showed that there was increasing thickness of loess on these terraces with increased height above the river. The surface is mapped as S5 which overlies sediments which are inferred to have formed before 73 ka (Berger et al, 1996). This pattern suggests that the location of the Kowai River (SB) in its upper reaches has been relatively stable since the start of deposition of the first loess sheet, that the river is subject to continuing base level lowering and that sea level has not been to that level since at least the deposition of the first loess sheet began. Continued uplift of the Kowai Anticline is supposed to generate alluvial fans along its margin. These alluvial fans are inferred from a small number of bore logs on the upper downlands which are dominated by fine grained material, considered to be similar to that shown in Figure 2.12.

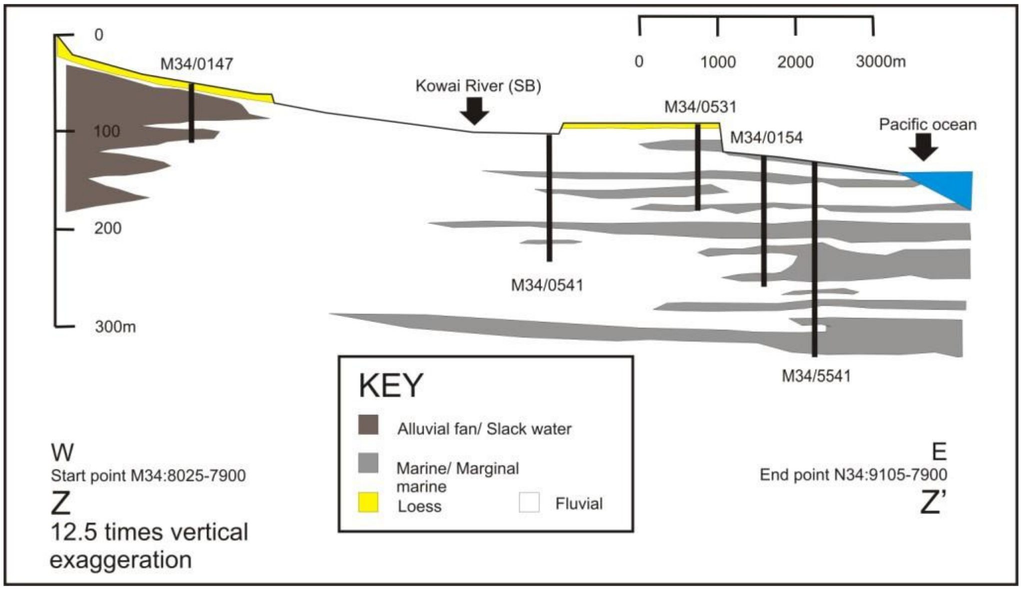

Figure 2.24 A simplified lithofacies interpretive cross section through the Kowai zone showing the main depositional environments. Location of the cross section is shown in Figure 2.23.

2.5.2 Waipara zone

A simplified interpretative lithofacies cross section of the sedimentary structure of the Waipara zone is shown in Figure 2.25.

The sediments in the Waipara Basin are though to have been formed from fluvial and slack water deposits (i.e. swamps and lakes) with contributions from alluvial fans on the margins of the basin. As the margins of the basin have been uplifted material is exposed to erosive agents which redistribute the material down slope. This has exposed Tertiary and Kowai formation sediments which presumably comprised the material within these fans. The Waipara fan dominates the centre of the basin, which tapers away from the current location of the river towards the basin margins. At the low points of the Waipara fan some of the smaller fluvial systems flow and deposit material (Kowai River (NB) and Omihi Stream). When the Waipara River aggrades these systems are interpreted to be incapable of keeping pace and therefore are occasional likely to be impounded. The Waipara Downs fan system however has been able to keep pace with the aggradation in the Waipara, evident from the intercalated deposits seen along the Waipara River.

The distribution of surfaces around the basin adds weight to the "bowl" conceptual models of Loirs (2000) and Lloyd (2002). The geomorphology of the Waipara Basin indicates that there has been at least two phase of aggradation by the Waipara River, followed by down cutting. The remnants of these aggradations are persevered on the margins of the Onepunga Anticline and the Teviotdale hills. In the Waipara Basin there are a number of active structures (Broomfield Fault, Boby Creek Fault and the Mound Fault) that are deforming the basin fill (Appendix 2f).

There is no evidence of marine intrusion into the Waipara Basin during the late Quaternary. It is proposed that this is due to continued tectonic uplift of the structures surrounding the basin.

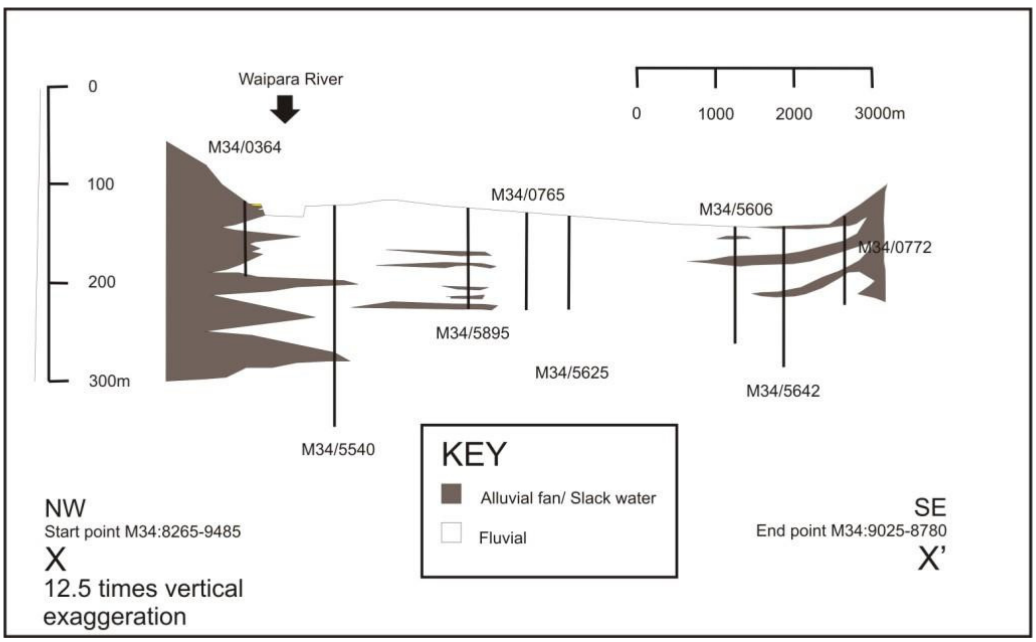

Figure 2.25 A simplified lithofacie interpretive cross section through the Waipara zone showing the main depositional environments. Location of the cross section is shown in Figure 2.23.

2.6 Chapter summary

A geomorphic map has been constructed of portion of the study area. Nine geomorphic surfaces have been identified ranging from modern to surfaces abandoned >73 ka. The map has been constructed using Landcare Research Ltd soils maps and field observations with a limited soil survey programme. Bore logs have been used to ascertain the geology beneath these surface and simplified models are proposed to explain the distribution of sediments found.

A hammer and plate seismic survey has been conducted to confirm that the terrace rise on the Southern side of the Amberley Swamp is a fault, informally named the Broomfield Fault, which clearly shows significant Quaternary uplift and deformation across the Waipara Basin with probable implications for groundwater flow. Line 3 also indicates tilting in a direction across the basin axis, probably associated with the propagation of the Onepunga Anticline driven by the Bobbys Creek Fault at depth. The emergence of Teviotdale gravels and the S3 surface at the Mound also indicate uplift parallel to the Waipara Basin axis and bisecting the basin.

Stream gradient index analysis (Hack, 1973) has been used to examine the location of any emerging structures within the Kowai Zone. This resulted in better definition of the known faults (Ashley & Loburn faults and the probable presence of the Teviotdale Anticline fault, an extension of the Omihi Fault system down the East side of the Waipara Basin). Stream gradient index also proved to be useful in defining geomorphic surfaces. Knick point migration relative to the margins of the topographic surfaces does not appear to be significant. The geometry of the streams and surfaces in the upper catchment of the Kowai River (NB) has been used to infer tilting and activity of the Broomfield Fault and Kowai Anticline. The nature of the boundaries and surfaces underlying the cover sediments varies with implications for their mode of formation and potential to be truncated or become buried downslope. In particular the nature of surfaces of similar age in the Kowai and Waipara zones tend to be contrasting. The former may be more influenced by the effect of marine interaction on the open coastline. In the enclosed Waipara Basin fluvial processes appear to be dominant.

3 Chapter three: Hydrology and Hydrogeology

3.1 Introduction

For the purpose of this chapter surface water information was used to obtain an understanding of losses and gains from surface water sources to groundwater. For the Ashley and Waipara Rivers existing information is summarised, whereas for the Kowai River and Saltwater Creek streams instantaneous and visual gauging programmes were initiated to gain a better understanding these surface water bodies. Springs that are listed on Environment Canterbury's wells database were examined. Springs were used to gain an understanding of localised groundwater flow directions.

Pumping test and step test data have been extracted from the Environment Canterbury's wells database to gain an understanding of the hydraulic properties in the study area. The results from selected pumping tests are discussed in terms of transmissivities and hydraulic resistance (K'/B'). Water levels from selected wells are presented and discussed in terms of groundwater recharge.

3.2 Hydrology

3.2.1 2007/2008 weather

Throughout Canterbury, as for much of the country, the Summer of 2007/2008 was particularly dry. As a result, a number of wells in the study area that are monitored monthly by Environment Canterbury were recording their lowest water level ever for that period (Martin and Williams, 2008. M34/0497 in Figure 3.1). In February 2008 the Minister of Agriculture had been dispatched to North Canterbury to discuss the drought with local farming representatives. That week approximately 100 – 135 mm of rain fell in the study area (per com. R Belcher and D Clark, 2008).

During the period February to July the weather was fairly typically for the study area. On the 31 July/1 August 122 mm fell in Amberley (Figure 3.1), 185 mm at Hurunui SH1 and 225 mm in Lowry Hills, Waiau (ECan, 2009). This rainfall caused widespread surface flooding throughout the study area (Appendix 3a) and beyond, with houses in Amberley and Sefton being flooded and residents of Amberley Beach being evacuated.

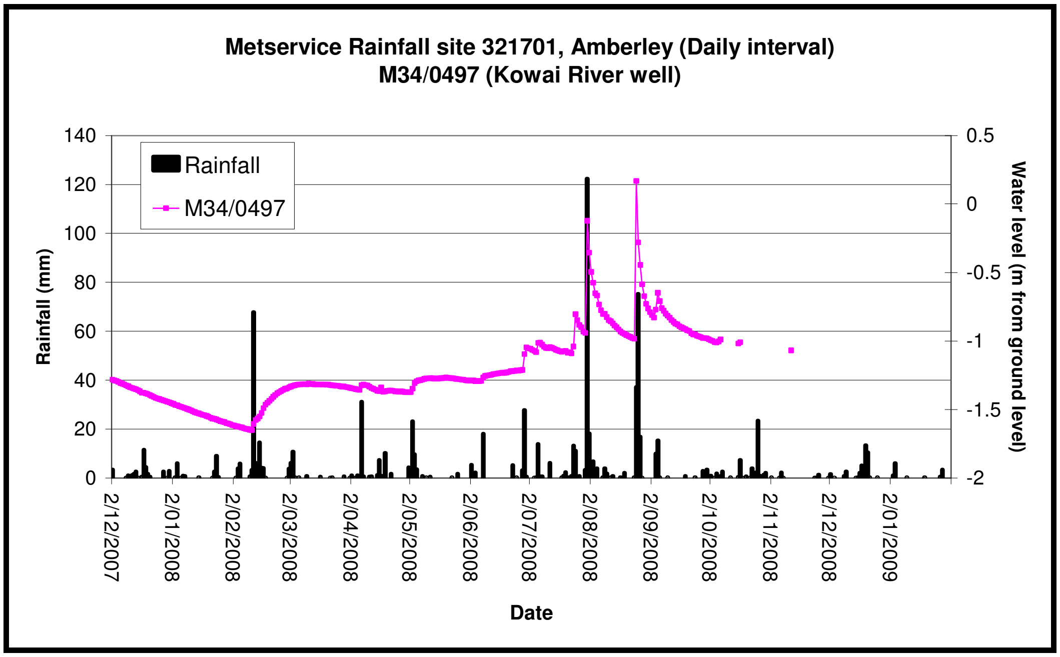

Figure 3.1 Daily rainfall record for Met services Amberley station and water level data from M34/0497 (5m deep) located within 100m from the Kowai River (NB). Rainfall data covers the period 2/12/07 to 31/1/09.

During the period 25 – 27 August 2008 another significant rainfall event occurred, with a total of 130 mm of rain being recorded at Amberley (Figure 3.1, Appendix 3a). Again significant surface flooding occurred throughout the study area (Appendix 3a) with homes in Amberley being flooded for the second time in a month. From September until the end of the year was relatively dry, with only 125 mm of rain being recorded at Amberley (Figure 3.1). The annual rainfall total for Amberley was 747 mm; with 50% of that total falling in the three events (average for this site is 673mm based on 97 years of data).

3.2.2 Visual gauging programme

In March 2008 a visual surface water flow gauging programme was initiated to gain a better understanding of the hydrology of the region. Of particular interest was the hydrology of the Kowai zone where little work had been done previously. 48 sites were monitored including all the Kowai River instantaneous gauging sites (Figure 3.2). The visual gauging was conducted simultaneously with the weekly stable isotope sampling and involved taking photos of streams/rivers for later analysis. Initially the intention was to estimate the flows at these sites however it was later decided to use this information in a qualitative manner. This was due to the large errors involved in estimating flows (errors would be in the order of 100 – 300%) caused in part by the very large variations in flow (section 3.2.1).

Figure 3.2 Spatial distribution of visual gauging sites. Sites are coloured on the basis of percentage of the time the site was flowing when visited during 2008. Also shown are the approximate locations of selected instantaneous gauging sites for the Waipara and Ashley Rivers.

Figure 3.2 illustrates that there was permanent flow in the Saltwater Creek catchment, in the upper part of the Kowai River (NB) and tributaries, along the Kowai River

(NB) below Amberley, Omihi Stream, Fox's Creek and small stream flowing from Ashley forest. The Kowai River (SB) often had flows at the top end (>75% of the time) with flows occurring less often downstream. Except for two sites, streams leading from Ashley forest were intermittently flowing.

Figure 3.3 shows the percentage of the visual gauging sites flowing per visit plotted against rainfall. This figure shows that in Autumn there were a relatively constant proportion of sites flowing and that Winter rainfall is more likely to contribute to stream flows, presumably as a consequence of decreasing ET rates and increasing soil moisture content. During Spring/Summer the proportion of streams that were flowing decreased regardless of the rainfall.

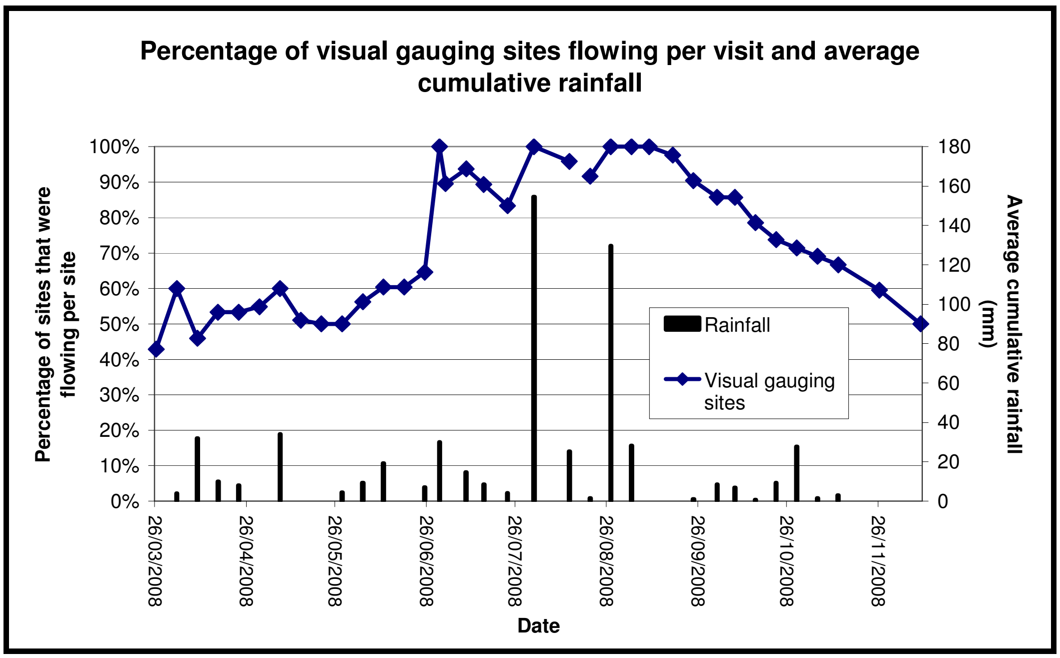

Figure 3.3 Percentage of visual ganging sites that were flowing during 2008 and average cumulative (weekly interval) rainfall for the two rain gauges installed in the study area for this project.

3.2.3 Instantaneous gaugings (Kowai River)

A total of six gauging runs were completed on the Kowai River during the period April – November 2008. The purpose of the gaugings was to indicate where losses and gains may be occurring during different flow regimes to gain a better understanding of the surface water/ groundwater relationship. The majority of the gaugings were conducted by Martin Webb (Senior Hydrological officer, Environment Canterbury) with assistance from the author.

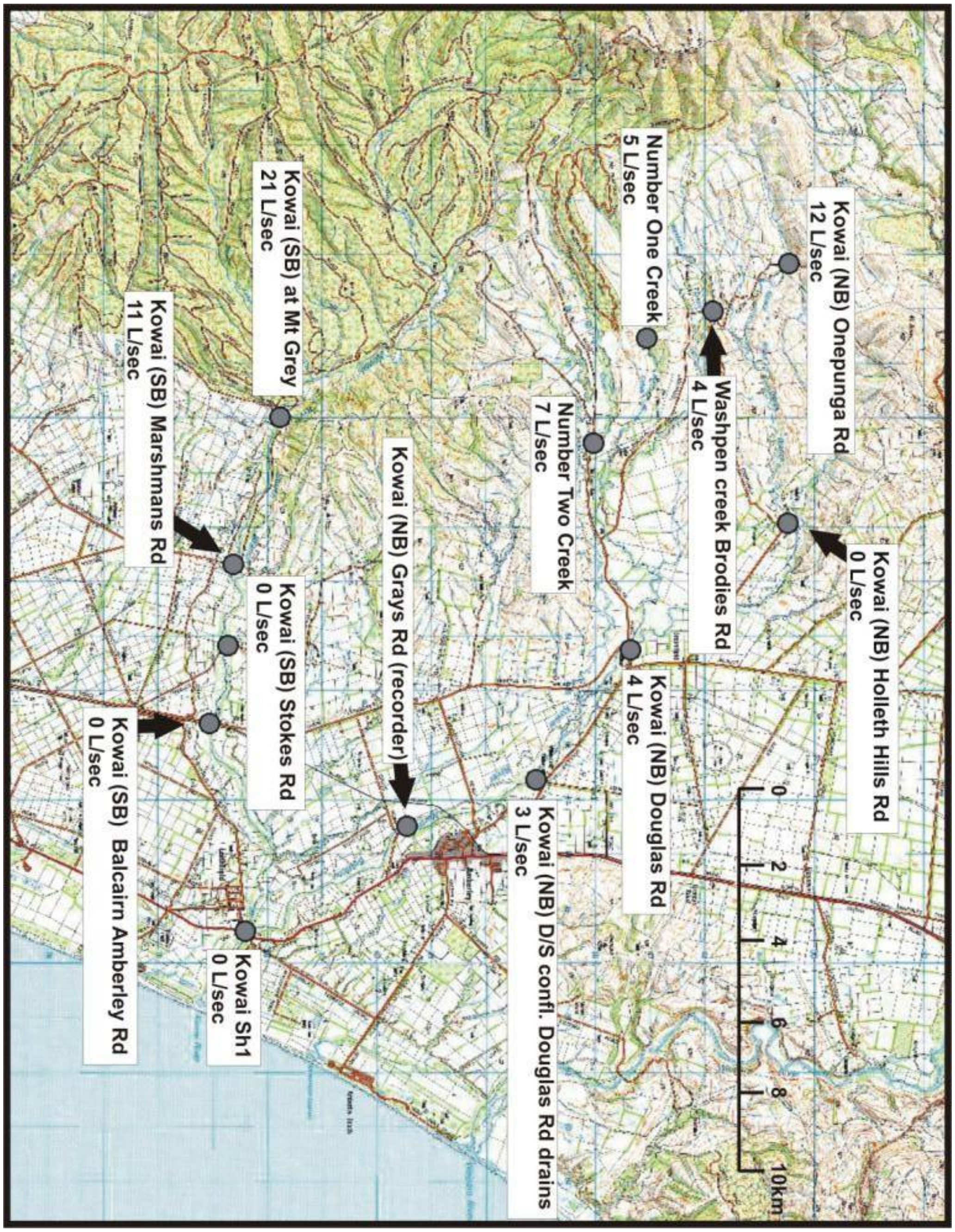

Figure 3.4 Location map of instantaneous gauging sites for the Kowai River. Flow rate below site ID is the median value of the three Autumn/Summer gauging runs.

For the first gauging run ten sites were gauged. However after subsequent discussions with landowners a further two sites were added; Number One and Two Creeks (Figure 3.4). These sites where added because it was reported that both these sites flowed all year round in most years and contributed to downstream flows.

Gaugings were conducted with OTT and OSS propellers set at 0.6 of the depth of water, using the velocity – area method and the standard river gauging procedures as outlined in the NIWA stream gauging manual. Differences in flows of ± ≥10% are considered significant (NIWA, 1996).

No attempt has been made to naturalise the data set. This is because there is only a small amount of water abstracted from surface water takes and from hydraulic linked wells (Appendix 3b) and there is no reliable water use data for the study area.

3.2.4 Instantaneous gauging results and interpretations

The results from the six gauging runs are shown in Figure 3.5 and Table 3.1. The results from the gauging runs conducted in April, May and November are reasonably similar. The median of these gaugings is taken here as an estimate of base flow (Figure 3.4). The median value was used as it is less affected by extremes.

From Table 3.1 and Figure 3.5 we can see that for the Kowai River (SB) the April, May and November gaugings had a similar pattern in that there was flow at the most inland gauging sites which was quickly lost to groundwater downstream. The November gauging was slightly different in that it had flow at Balcairn Amberley Road, which went dry just downstream of the gauging site (per com. M Webb, 2008). The June gauging showed that downstream of Stokes Road significant losses from the river occurred. The July run was conducted after the Kowai River began flowing along it entire length and the August gauging after the 1st major Winter rainfall event (Table 3.1). Both gaugings showed slight gains at Marshmans Road and then no significant differences downstream excluding SH1.

Summing the contributions from both branches and computing a percentage difference in flow at SH1 revealed that for the August gauging run there was a 25% gain. The difference is likely to be from small ephemeral streams that only flow after a large amount of rain has fallen and that feed into the Kowai River upstream of SH1. For the July run there was no significant change in flow, but for all the other gaugings runs there was a loss at SH1 ranging from 77 – 100% of the flow.

For Number One, Two and Washpen Creek there was always a flow at these sites but gauged flows were always less than 100 L/s (Table 3.1 and Figure 3.5). Number One Creek flow varied little, while the other two sites responded to Winter rainfall. Summing the contributions from these three sites plus Onepunga Road and comparing them to the Douglas Road (the confluence of these sites) revealed that only in August was there a net gain (27%). Otherwise there was always a loss from these creeks /river relative to Douglas Road.

Table 3.1 Results from instantaneous gaugings conducted on the Kowai River and major tributaries. Value in blue bold is an estimate. The top value was obtained from the gauging; the bottom number is the % difference between that site and the previous upstream site. NS = not significantly different. NB Kowai at SH1 is shown twice.

Site ID	11 Apr	15 May	12 Jun	13 Jun	3 Jul	15 Aug	25 Nov
	L/s % difference						
Number Two Creek		7		26	79	81	7
Number One Creek		5		7	14	19	***4***
Washpen Creek Brodies Rd	1	6		14	87	69	4
Kowai (NB) Onepunga Rd	9	12		22	69	85	15
Kowai (NB) Holleth Hills Rd	0 -100%	0 -100%		0 -100%	40 -42%	60 -29%	0 -100%
Kowai (NB) Douglas Rd	4	1		42	199 398%	347 478%	14
Kowai (NB) D/S confl. Douglas Rd drains	3 -25%	3 300%		5 -88%	190 NS	523 51%	66 371%
Kowai (NB) Grays Rd (recorder)				5 NS			112 70%
Kowai SH1	**0** -100%	**0** -100%		**0** -100%	**490** 158%	**1124** 115%	**16** -86%
Kowai (SB) at Mt Grey	14	34	234		307	323	21
Kowai (SB) Marshmans Rd	1 -93%	11 -68%	235 NS		350 14%	368 14%	13 -38%
Kowai (SB) Stokes Rd	0 -100%	0 -100%	211 -10%		321 NS	389 NS	0 -100%
Kowai (SB) Balcairn Amberley Rd	0	0	156 -26%		317 NS	377 NS	4
Kowai SH1	**0**	**0**	**0** -100%		**490** 55%	**1124** 198%	**16** 300%

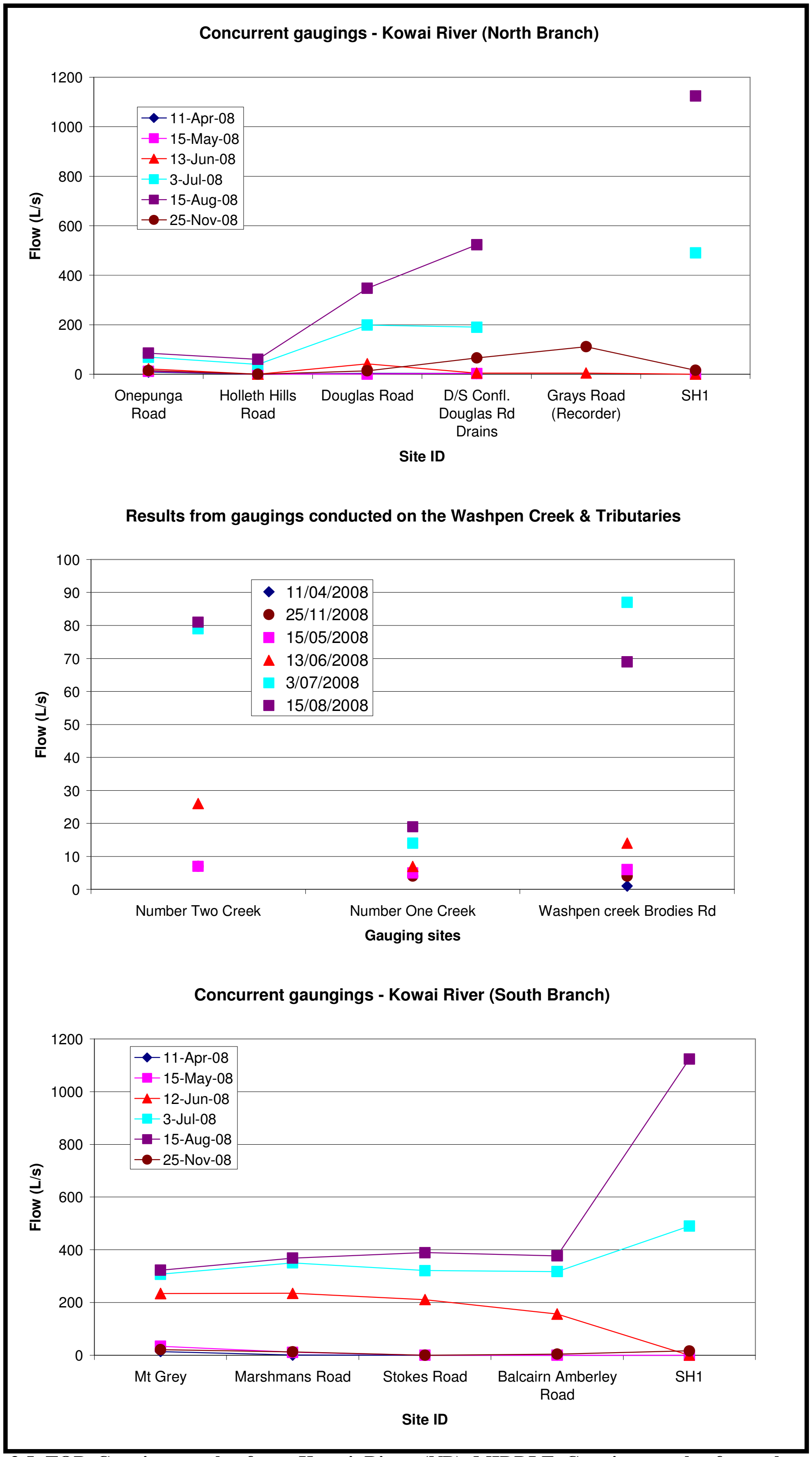

Figure 3.5 TOP Gauging results from Kowai River (NB) MIDDLE Gauging results from the major tributaries feeding into Kowai River (NB) BOTTOM Gauging results from Kowai River (SB).

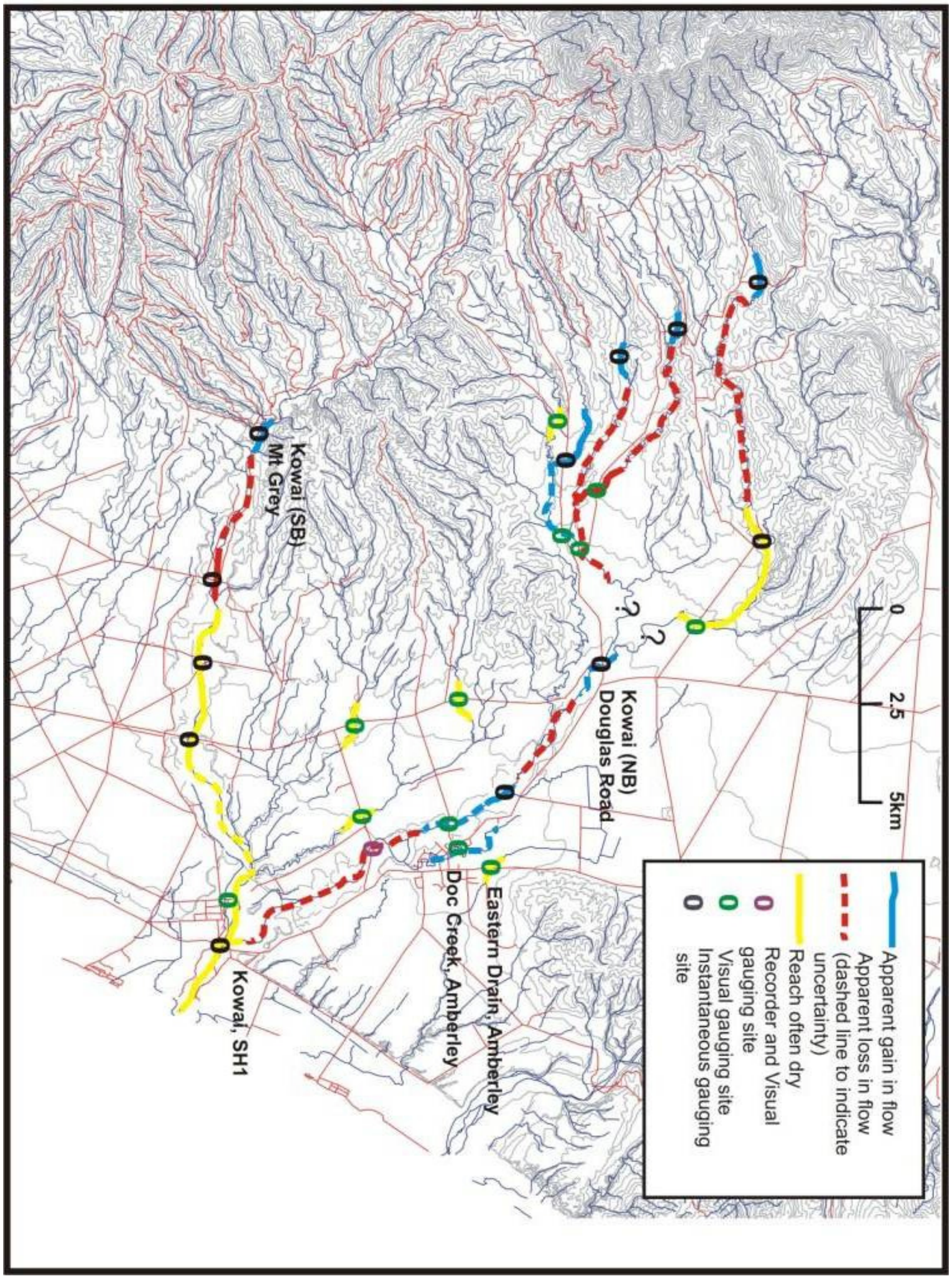

Figure 3.6 Interpreted pattern of loss and gain from the Kowai River during Summer - Autumn.

For the Kowai River (NB) the April, May and June gaugings showed a relatively similar pattern. Downstream from Onepunga Road all the water was lost from the River. At Douglas Road there was always a flow but this dried up several hundred meters downstream (except for the June run). Just before the next gauging site (confluence with the Douglas Road drains) there is a permanently flowing spring.

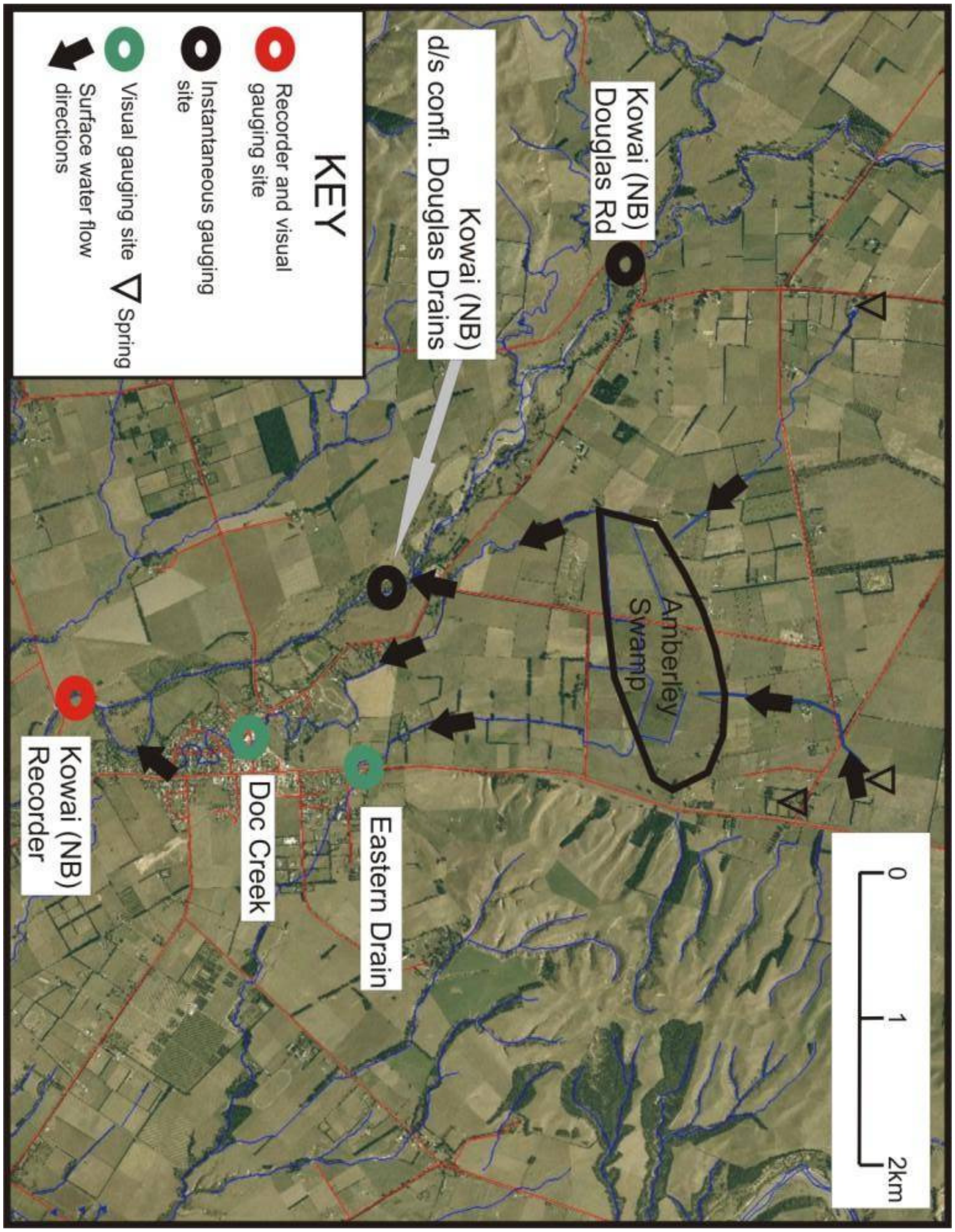

Figure 3.7 Map showing major springs and drains leading into the Amberley Swamp and the discharge from the Swamp.

Visual gauging showed that there was flow in the river until at least the recorder site. It is likely at least some of this flow was contributed by Doc Creek (Figure 3.6). For the July and August runs between Onepunga Road and Holleth Hills Road there was always a loss in flow. Downstream of Douglas Road in July the flow was maintained all the way to SH1. For the August run flow increased at the confluence of the Douglas Road drains signifying input from the drains (see next section).

Following the significant rainfall that fell in Winter (Figure 3.1) all the ephemeral streams and intermittent springs in the study area began to flow. In the South of the Waipara Basin these streams flowed into the Amberley Swamp (Figure 3.7). The two drains that lead from the swamp were incapable of keeping up with the input and the swamp filled (Appendix 3a). The Amberley Swamp did not dry up till December 2008.

3.2.5 Ashley River

Recharge from the Ashley River was described by Bowden et al (1982) and more recently losses and gains from the Ashley River during low flows were described by Chater (2004).

Generally below the gorge to Bowicks Road (on the Eastern side of the Mairaki downs) there is a loss from the river to groundwater as the river emerges onto the plains. From Bowicks Road to Number 10 groyne (9 km above Rangiora) there is net gain to the river from groundwater. This gain in flow is additional to inputs from Garry and Okuku Rivers (Chater, 2004). Below Number 10 groyne to Lowes corner Chater (2004) estimates a loss of >1100 L/s from the Ashley River to groundwater (Figure 3.2). Bowden et al (1982) estimated a loss of 2500 L/s in these reaches. Below Lowes corner to SH1 there was a net gain to the river (Figure 3.2).

3.2.6 Waipara River and tributaries

Losses and gains from the Waipara River and tributaries at low flows were described by Chater (2002, 2003) and at low – medium flows by Lloyd (2002).

Generally in the upper catchment to the Stringers Bridge there is an increase in flow due to tributary inputs (Figure 3.2). There is some contention about losses and gains below Stringers Bridge to the site downstream of the Omihi Stream confluence with the Waipara River. Lloyd (2002) showed that at medium flows there is a gainI in this reach and suggests that at low flows the flow is maintained through this reach. Chater (2002) suggested where there is a medium – high flow in the Waipara River the Weka Creek is likely to be flowing along its entire length (usually dry at the confluence with the Waipara River, see section 3.2.2) and contributing to the flow in the Waipara River. Chater (2002, 2003) suggest that at low flow there is a slight loss from the river (average loss of 40 L/s). Visual inspection of all the simultaneous gauging runs conducted on the Waipara River show there is complex pattern of losses and gains that appears to vary with flow rates.

The Waipara River flows significantly increase downstream of the confluence of Omihi Stream, particular at low flow rates (Chater, 2002). There is generally a slight increase in flow from Omihi Stream to the recorder at the Teviotdale. Below the Teviotdale recorder to the mouth the Waipara River there is a significant loss of water from the river (Figure 3.2).

At low flows the Weka Creek tends to increase in flow downstream until it enters the Waipara Basin. As it crosses the gravels all the water is lost to the groundwater system (Lloyd, 2002). Home Creek behaves similarly to Weka Creek in that in its upper catchment flows generally increase until it enters the basin at which point most of its flow is lost (Llyod, 2002). Omihi Stream increases in flow downstream, particular downstream from the confluence with Home Creek and at Gleneray Farm (Llyod, 2002. Glenray Farm is located near the visual gauging site for Omihi Stream shown in Figure 3.2). At both these locations there are numerous springs (Loris, 2000).

3.2.7 Springs

Shown in Figure 3.8 is the spatial distribution of all the mapped springs in the study area. The majority of the spring mapping was conducted by summer students employed by Environment Canterbury (Katie Bristow and Jonathan Claridge). The springs were mapped using the methodology and terminology of Earl (1998a, 1998b). The priority for the spring mapping was the Kowai zone where a large number of springs existed but had not previously been located and described (Appendix 3c). Before this study on Environment Canterbury's wells database there were 11 springs recognised in the Kowai zone, now there are 91.

From Figure 3.8 we can see that there are a large number of springs in the Saltwater Creek area. This was expected given the visual gauging observations (section 3.2.2) and the soils present (section 2.2.2). It is likely there are still springs in these areas that are yet to be mapped.

Figure 3.8 Map showing the locations of all the mapped springs in the study area and beyond.

There are ten mapped springs near the base of the marine cut terrace (section 2.2.3) and within Westward entrenching gully systems between the Waipara mouth and Saltwater Creek. The springs at the base of the marine terrace occur usually as seepage emitting from small colluvial fans. These springs are likely to have formed in response to the abrupt change in topography exposing the water table to the ground surface. The gullies forming in the marine terrace tend to have a spring near the eroding head suggesting a link between gully erosion and spring occurrence. There are more springs in this area than those shown in Figure 3.8.

On the downlands six springs have been located. These springs occur in relic channel features or near active streams which suggests that these springs are occurring where the loess is thin or absent. It is likely that there are more springs located in this region than recognised here.

There are springs located along the Eastern and Northern margins of the Teviotdale hills (see section 3.2.4, Appendix 3a). These springs have not been described (Earl, 1998a & 1998b) so are not shown on Figure 3.8.

Figure 3.9 Photograph of the M34/5879, a spring emanating from the Mount Brown Formation.

The Kowai River (NB) at Onepunga Road is sourced from a spring (M34/5879) which emerges from the Mount Brown formation. Here the Mount Brown Formation is exposed on the Southern limb of the Onepunga Anticline with bedding dipping to the Southeast at about 18 – 30º. The Kowai River (NB) flows along the valley floor overlying this limb. The geomorphic mapping suggests that in the recent past the river must have incised into the Mount Brown Formation. At the point of incision into the Mount Brown Formation the water is allowed to flow out to the surface (Figure 3.9). Because of the geometry of units involved, it is likely that this spring is recharged from rainfall falling on the top of the Onepunga Anticline.

During the project springs in the lower reaches of the Omihi Stream were visited. Loris (2000) was the first to describe these springs. It was noted during the visit that many of the springs were located on the Western side of the stream, and many of the springs were located above the level of the stream. This geometry implies these springs are recharged from the West and North.

There are a number of springs located at or near the base of the lower terraces of the Waipara River but above the river. These are more springs in this area that are shown on Figure 3.8. The locations of these springs show that groundwater is flowing towards the river, probably because of the abrupt change in the topographic gradient.

3.3 Hydrogeology

3.3.1 Aquifer definition

This study adopts the aquifer definition (Fetter, 2001. page 552) being; "*rock or sediment in a formation, group of formations, or part of a formation which is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs*".

This definition is used here because;

- It intentionally covers a broad range of geological materials.
- It emphases the role of hydraulic properties of materials in groundwater movement.

It is however essentially an economic definition without regard for environmental outcomes. It does not provide technical criteria for distinguishing between aquifers, rather it distinguishes qualitatively between aquifer and non-aquifer depending on the user's intention towards the resource.

For this project aquifers are defined on the basis of geological formations. It is acknowledging however that it is likely that there is flow of groundwater between formations and that buried channels probably play a significant role in local groundwater flow within a basin fill system (Dann et al, 2008).

3.4 Hydraulic properties

The purpose of this section is to establish likely hydraulic properties for the basin fill sediments and to indicate the connectedness of the groundwater system.

3.4.1 Yield and specific yield

Maximum (pumped) yield and specific capacity values on Environment Canterbury's wells database are mostly acquired from drillers who conduct a short duration step test to estimate the yield from the well (often only one step and often <30 minutes). Not all wells in the database have this basic data. Pumping rates are typically estimated from an orifice or bucket and a watch. Maximum yield is not the maximum yield that can be obtained from that well but rather the maximum rate the well was pumped at during the test. For wells with multiple steps (occasionally multiple tests) the lowest pump rate recorded on the oldest date is used to calculate the specific capacity (SC = yield ÷ drawdown). The oldest date is used because well performance can deteriorate with time i.e. due to sediment clogging the screen. However it should be noted that specific capacity can vary depending on the flow rate as a result of the well efficiency.

Figure 3.10 is a plot of maximum yield and specific capacity plotted against depth. For the maximum yield graph there is a distinct trend towards greater yield with depth in the Waipara zone, while in the Kowai zone the greatest yields are obtained from depths < 50 mbgl. Overall in the Waipara zone specific capacities tend to decrease with depth, though there is an apparent peak at -100 mbgl. This indicates that the increased yield with depth pattern in the Waipara zone is a result of greater available drawdown within the well. The specific capacity plot shows that in the Kowai zone the largest values are again from <50 mbgl. Furthermore the specific capacity plot x axis has been set to a maximum of 20 L/s/m so not shown in Figure 3.10 are an additional 12 wells in the Kowai zone with specific capacities >20 L/s/m (up to 160

L/s/m) at depths <24 mbgl plus a single well in the Waipara zone (-3 mbgl, SC = 60 L/s/m).

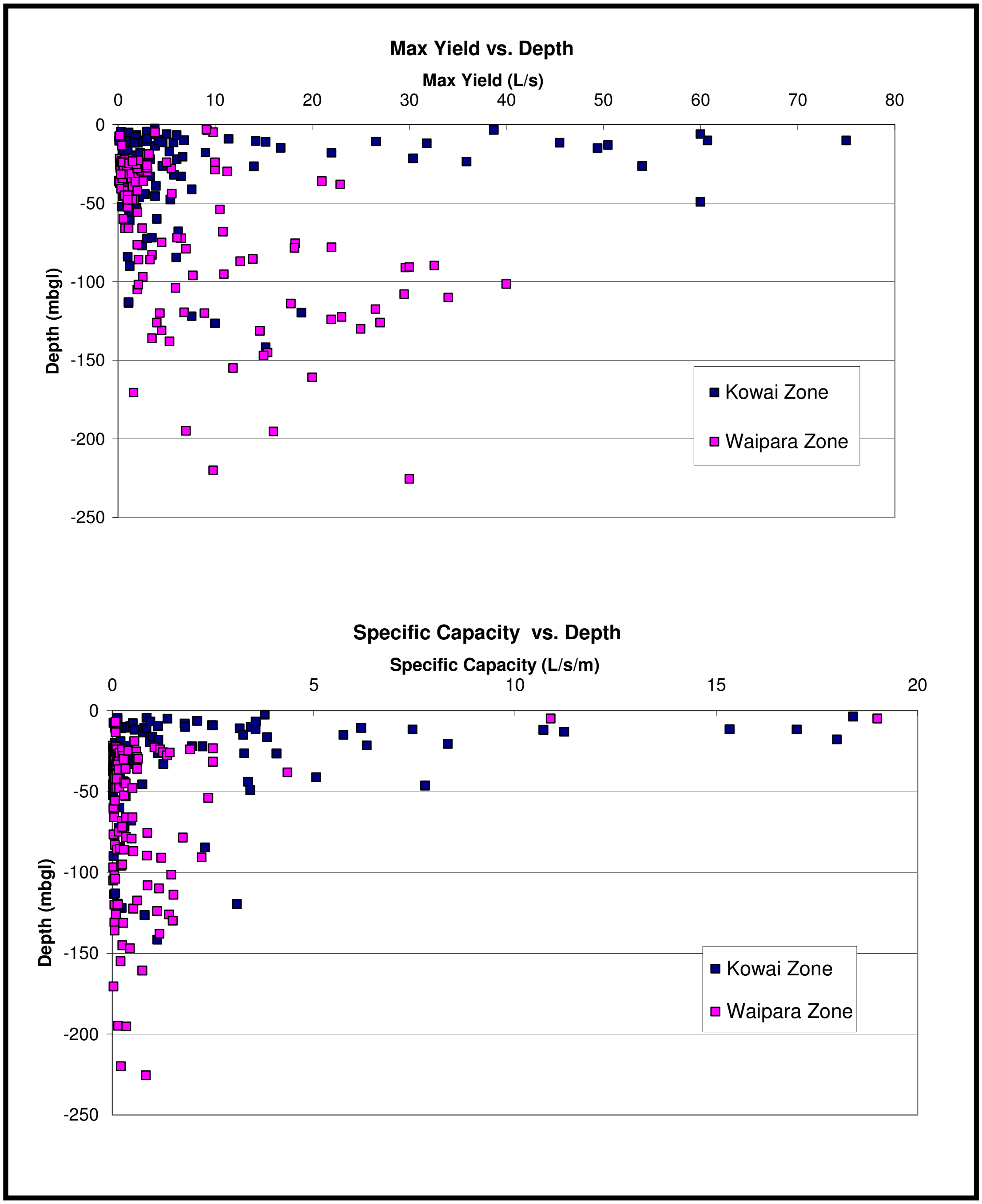

Figure 3.10 TOP: Maximum (pumped) yield (see text) plotted against depth for wells in the Waipara and Kowai zones. BOTTOM: Specific capacity against depth for well in the Waipara and Kowai Zone. Note the scale on the x axis has set to maximum value of 20 L/s/m to provide greater resolution of the Waipara zone (see text).

Plotting the data spatially reveals that the higher specific capacities in the Kowai Zone occur in the Saltwater Creek area near the Ashley River, near Leithfield close to the Kowai River or downstream from the lower gorge of the Waipara River. This and the surface water gauging data presented in section 3.2 suggest these areas are receiving recharge from the rivers. The wells in the Waipara zone with the specific capacities >10 L/s/m are all less than 5m deep, located on the lowest terrace next to the Waipara River near the Waipara Township. These factors suggest that these wells are connected to the Waipara River. Specific capacities from wells near Weka, Home Creek and Omihi Stream are not sufficiently different from wells located away from these sources. This probably reflects the low and intermittent flows of these streams within the basin (section 3.2) and/or that some of the wells tested are not connected to these surface water sources.

3.4.2 Aquifer tests

Within the study area there have been a total of 19 constant discharge pumping tests conducted and recorded in Environment Canterbury's wells database (Figure 3.11 and Appendix 3d). Of this number, seven were either pumped for less than 900 minutes, had a Brooks reliability rating of four or more (Brooks, 1998, where 1 is good and 5 is poor), did not have a flow rate recorded or did not have an estimate for transmittivity. Averages, standard deviations for selected aquifer parameters and geometric mean for transmittivity for the other 12 aquifer tests are listed in Table 3.2. There were three aquifer tests conducted in the Kowai zone however none fitted the above stated criteria. Also shown in Table 3.2 are estimates from the Canterbury Plains using the same criteria as above except aquifer tests with a Brooks reliability of three or more were discarded. This was done because the Canterbury Plains dataset has a larger population.

Table 3.2 Geometric mean, average and standard deviation for selected aquifer parameters derived from aquifer tests conducted in the Waipara Basin and from the Canterbury Plains.

Area		Depth (mbgl)	T (m^2/day)	S	K/'B' (Day^{-1})	Q (L/s)	Duration (Minutes)
Waipara	Geomean		50				
	Average	-93	100	0.0006	0.0001	12	3756
	Std Dev	57	134	0.0008	0.0002	10	3185
	Count	12	12	6	2	12	12
Plains	Geomean		1405				

	Average	-62	3199	0.0106	0.0079	38	2212
	Std Dev	49	4776	0.0284	0.0113	24	1680
	Count	68	68	39	9	68	68

From Table 3.2 we can see that values for transmittivity in the Waipara Basin are quite low (ranging from 12 – 490 m^2/day, Appendix 3d) when compared to the tests conducted on the Canterbury Plains (range 51 – 31400 m^2/day, Appendix 3d). The contrast between Waipara Basin transmittivity values and the average Plains wells is large; using the Fetter's (2001) definition a (speculative) question would be: if the Waipara Basin gravels were located on the Plains would they be considered an aquifer? When this small set of transmittivity values are plotted against depth no apparent trend is apparent (Appendix 3d).

3.4.3 Pumping interference

Many of the aquifer tests in the Waipara Basin have been initiated to assess the potential effect of abstraction on existing users. Loris (2000) showed that pumping can affect neighbouring bores though not necessarily with the largest effect to the nearest well. Lloyd (2002) suggested that pumping from largely shallow (<30m deep) domestic bores on lifestyle blocks North of Amberley had a significant cumulative drawdown effect on the water table. Well interference is likely due to relatively high density of wells in sediments with low transmittivity.

N34/0316 (78.5m deep) was tested during Winter, pumped for 47 hours at 14 L/s (Lincoln Environmental, 2004). Three shallower wells were monitored; N34/0058 26 m deep 1150m away (from N34/0316), N34/0105 25m 990 m away and N34/0305 44m 750 m away. All the monitoring wells had a delayed respond (six hours before observable draw down occurred in the case of N34/0058) interpreted to be leakage from an overlying aquifer. Using the Hunt (2004) method an average K'/B' value of 0.02 day^{-1} was calculated (Lincoln Environmental, 2004). Interestingly N34/0058 had the largest interference effect, followed by N34/0105 and then N34/0305.

N34/0351 (220m deep) was tested during Summer, pumped for seven days at an average rate of 9.8 L/s (Aqualinc, 2008a). Five of the seven monitoring bores were pumped during the test. Aqualinc (2008a) did not recognise any obvious pumping effects in the remaining two other wells (N34/0047 27m deep 27m away, M34/0777 90m deep 1200m away).

M34/5623 (123m deep) was tested in Winter, pumped for 24 hours at an average rate of 14.1 L/s (Aqualinc, 2004). The closest well (M34/5629 131m deep 334m away) was clearly affected. M34/5567 (34m deep 693m away) was not affected as were none of the other observation bores (thought the remainder of the wells were >1900m away). K'/B' was calculated at 1 x 10^{-6} day^{-1}. M34/5633 (75m deep) was tested in winter, pumped for seven days at an average rate of 4.5 L/s (GPF, 2007). Only one of the five observation bores responded; M34/0799 30m deep 200m away. K'/B' was calculated at 2.73 x 10^{-4} day^{-1}.

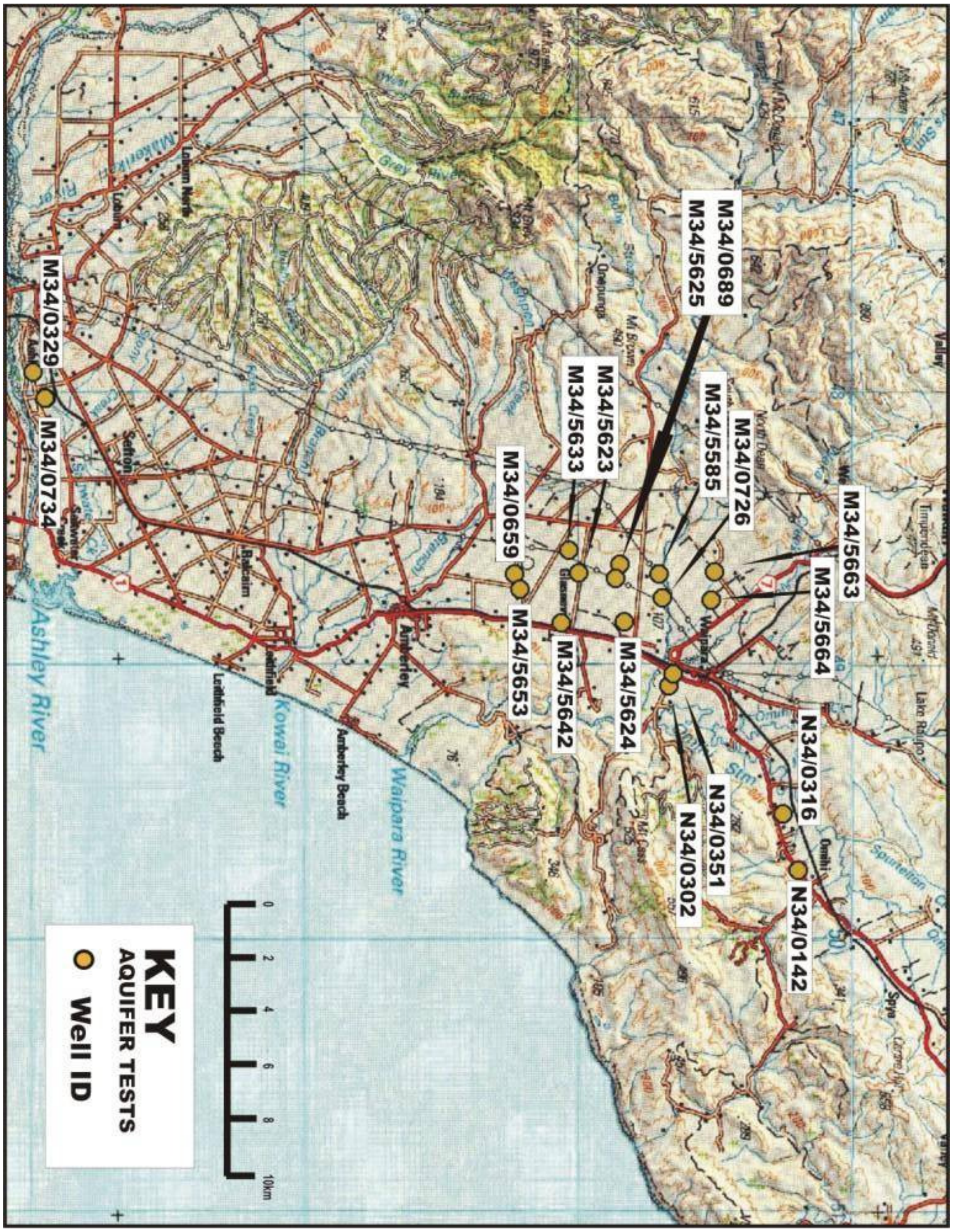

Figure 3.11 Spatial distribution of wells in the study area that have undergone constant discharge pumping tests. See Appendix 3d for details.

M34/5585 (83m deep) was tested in Summer for 42 hours at an average rate of 1.8 L/s (Aqualinc, 2008b). Two of the five monitored wells responded to the pumping; M34/5652 96m deep 824m away and M34/0684 26m deep <100m away. Two of the observation bores were pumped during the test while the automatic recorder in the remaining well malfunctioned during the test. The water level response in M34/0684 was unusual in that it rose when M34/5585 pump was started and decreased rapidly after the pump was switched off (the recorder was tested later at which point it was working normally). Aqualinc (2008b) concluded that this well was connected to the deeper well.

The interpretation from the aquifers tests described above is that there is potential for pumping interference within the Waipara Basin. Clearly in places deeper wells can affect shallower wells (Lincoln Environmental, 2004, Aqualinc, 2008b) due to vertical leakage, whereas some deeper wells seem to have no influence on the tested wells (Aqualinc, 2008a). This is due to the inhomogeneous sediments contained within the formational aquifers and supports the conclusions from section 2.3.

3.5 Water level observations

For this project 58 wells were monitored for groundwater levels weekly or monthly. These wells were located in the Southern half of the Waipara zone and in the Kowai zone. An additional 45 wells are monitored monthly by Environment Canterbury in the Waipara Basin (Figure 3.12). Manual water level data was collected with a volt meter type probe with errors of up to ± 2 cm. Recorder data was collected on Level trolls and processed in TIDEDA. All water levels are shown relative to ground level.

The intention of this section is indicate potential recharge sources by comparing the water level response in wells to rainfall and rivers data. In addition, longer term (>5 years) water level data from the Waipara zone is presented to indicate trends. The section concludes by examining the distribution of wells with artesian heads. Wells with artesian heads are assumed to be caused by water being pressurised between confining layers.

3.5.1 Kowai zone

Water levels from wells located near the Ashley River are shown in Figure 3.13. The water levels from the three shallower wells (<27m deep) are close to the ground surface. Water levels in M34/0703 and M34/5627 rose after rainfall while M34/0335 was relatively constant throughout the year. The proximity of these wells to the river and their high water levels imply a constant recharge from the Ashley River. In bore M34/5640 water levels responded after major rainfall events. Its proximity to the River suggests that it also is likely to receive recharge from the Ashley River.

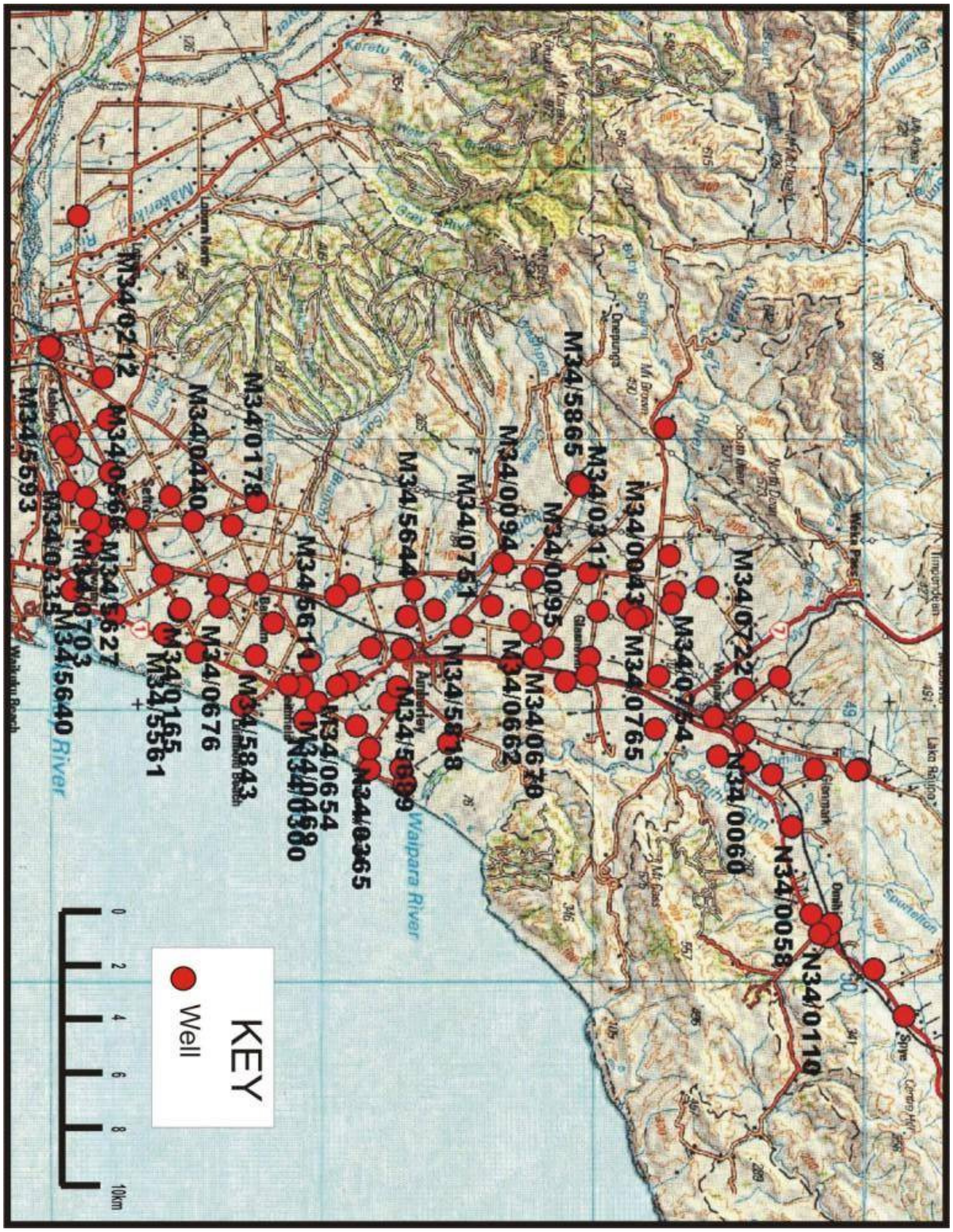

Figure 3.12 Spatial distribution of wells monitored by Environment Canterbury in the Waipara zone and wells monitored for this project.

In M34/5593 water levels did not respond immediately to rainfall, rather the water level in this well showed a smooth seasonal pattern. The bore log shows several silt/clay layers likely to be a continuation of the Kaiapoi artesian system (see section

2.2.2). The water level in this well has a strong correlation to M34/0734 (77m deep, R^2 = 0.99, Figure 3.14) and M34/0566 (46m deep, R^2 = 0.96, Appendix 3e).

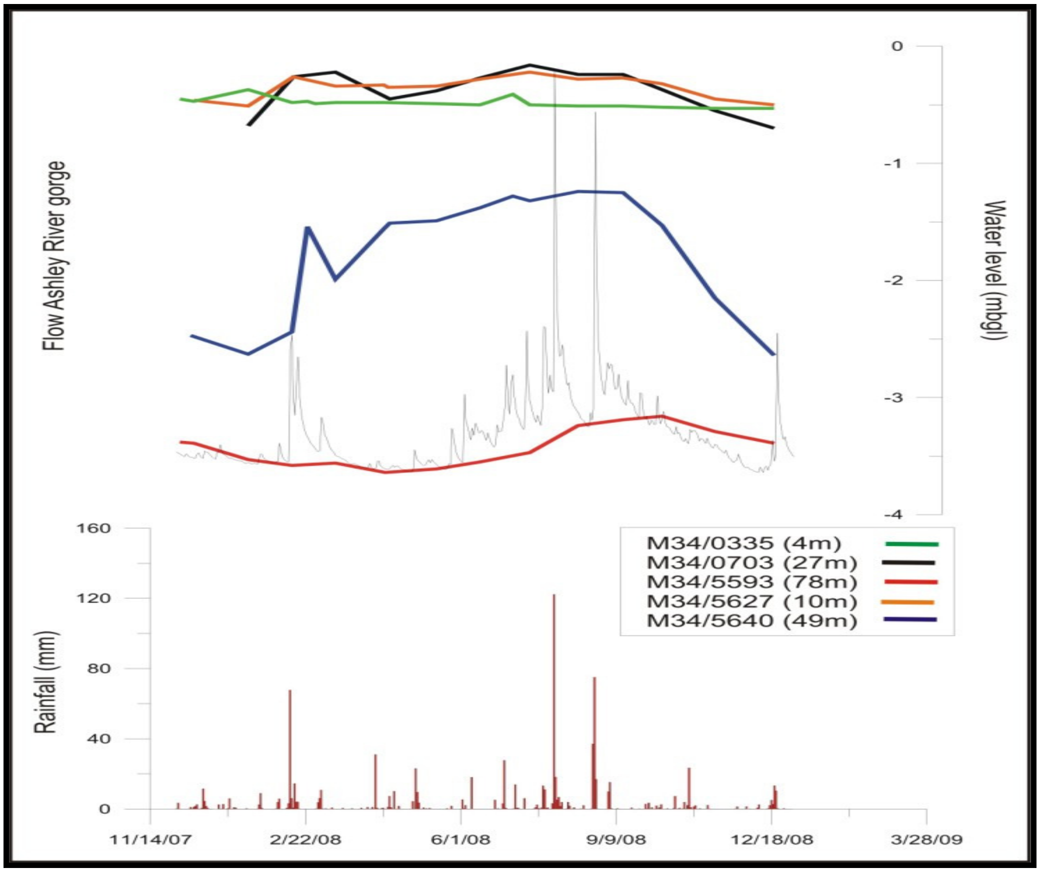

Figure 3.13 Selected water levels from wells located near the Ashley River. Rainfall data is taken from the Met service station at Amberley. Flow data is unprocessed data from the surface water recorder on the Ashley River at the gorge. The figure in brackets next to the Site ID is well depth.

Figure 3.15 shows selected wells in the Kowai zone. M34/0178 and M34/0212 are shallow wells located close to ephemeral streams. The water levels show an abrupt change in slope after rainfall. M34/0212 is located in the channel of an ephemeral stream and when the stream flowed it inundated the well. M34/0178 is likely to be connected to the nearby stream. N34/0365 is also a shallow well located near a drain by the coast. The water level in this well peaked several weeks after rainfall. It is interpreted that the well is connected to the drain which is partially fed from Eastern Drain and partially from springs emanating from the Marine cut terrace (see section 3.2.7). Well M34/5561 and M34/0566 have a relatively similar water level curve (R^2 = 0.48, Appendix 3e). Neither seems to respond immediately to rainfall but rather display a seasonal trend peaking in Winter/Spring.

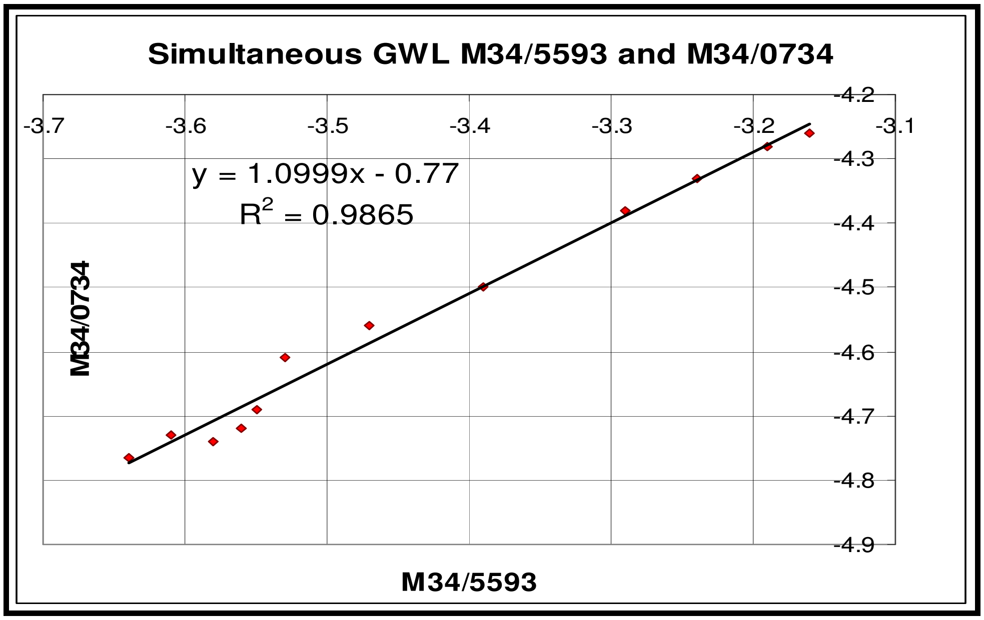

Figure 3.14 Simultaneous groundwater plot for M34/5593 and M34/0734

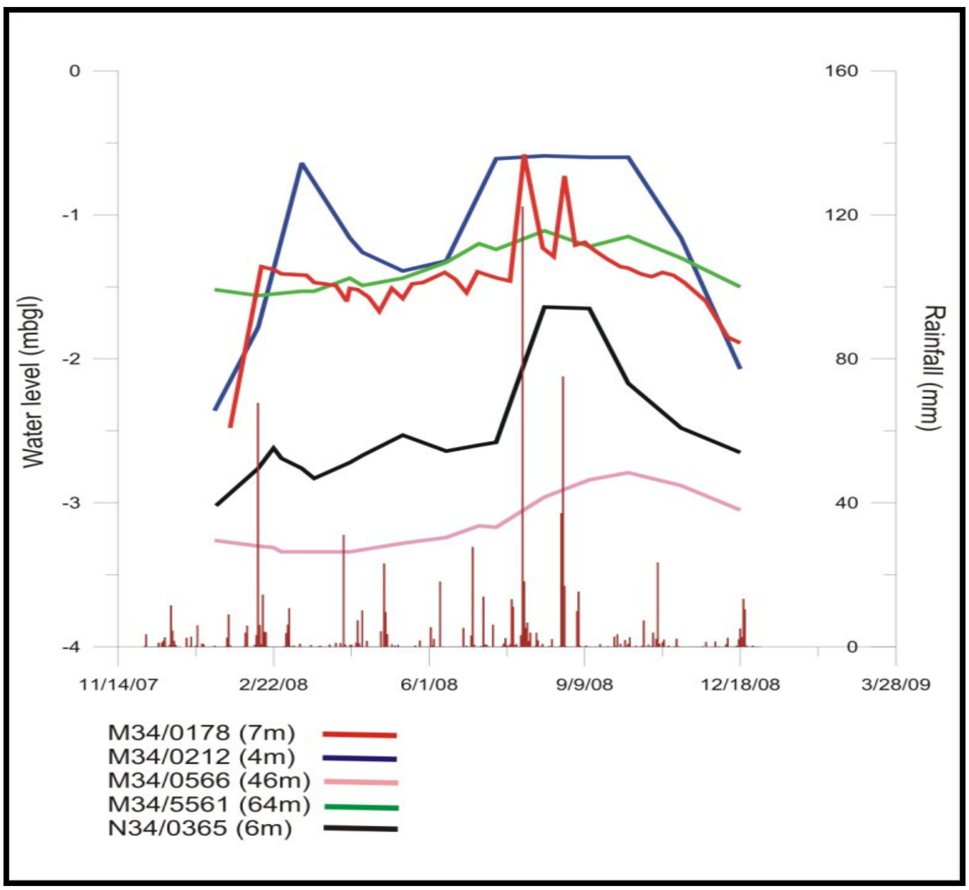

Figure 3.15 Selected water levels from wells located in the Kowai zone. Rainfall data is taken from the Met service station at Amberley. The figure in brackets next to the Site ID is well depth.

Figure 3.16 shows selected wells from the Kowai zone. M34/0440 and M34/0676 are located on the downlands and distant from any streams. Water levels in both rose after major rainfall events. This indicates rainfall recharge is occurring on the downlands. This is probably because recharge is occurring through macropores in the loess (Williams and Allman, 1969. Beven and Germann, 1982. Thorley and Ettema, 2007) or recharge may be occurring where loess is thin/absent. M34/0165 and M34/5843 are located near the Eastern limits of the downlands. Water levels rose immediately in both after the Winter rainfall, but peaked 4 – 5 weeks later. Not shown in Figure 3.16 are water levels from September and October for M34/0165 where this well became a flowing artesian well and could not be measured (150mm Ø PVC casing with a surface pump). This is interpreted to be a pulse of water flowing East/ Southeast from the downlands. The water levels in M34/5689 show small delayed rises after rainfall.

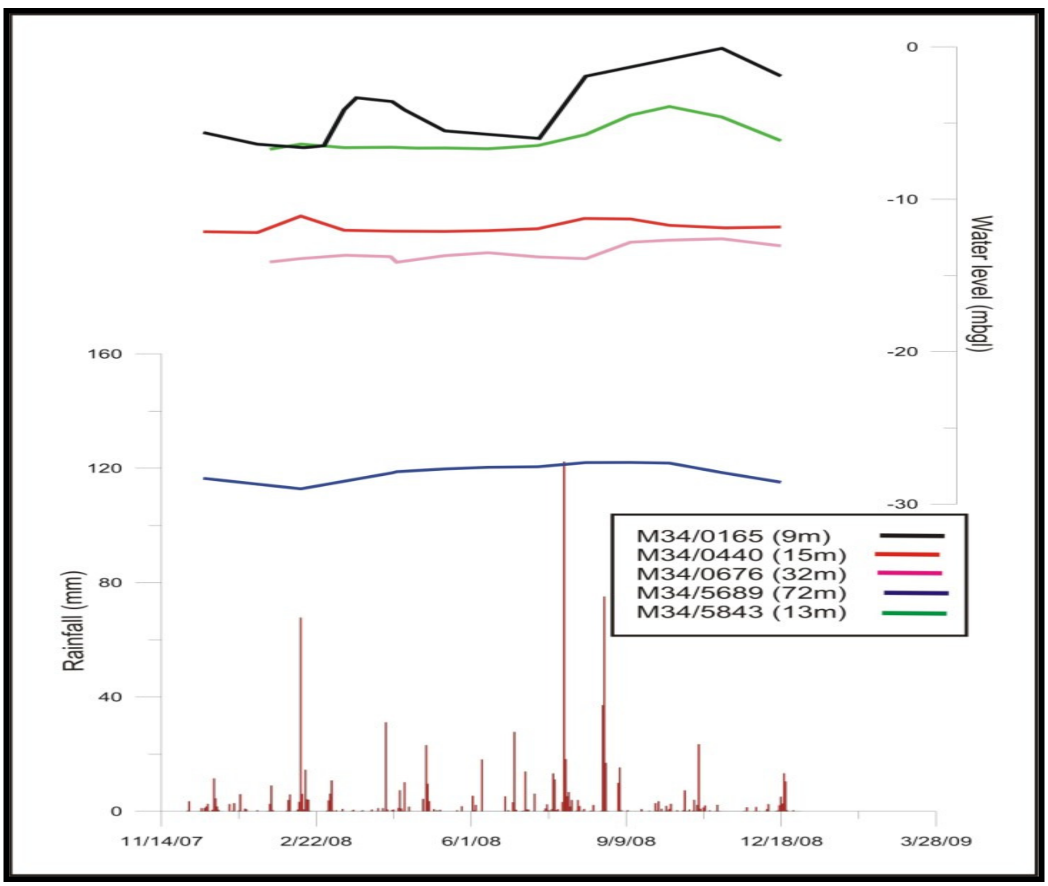

Figure 3.16 Selected water levels from wells in located in the Kowai zone. Rainfall data is taken from the Met service station at Amberley. The figure in brackets next to the Site ID is well depth.

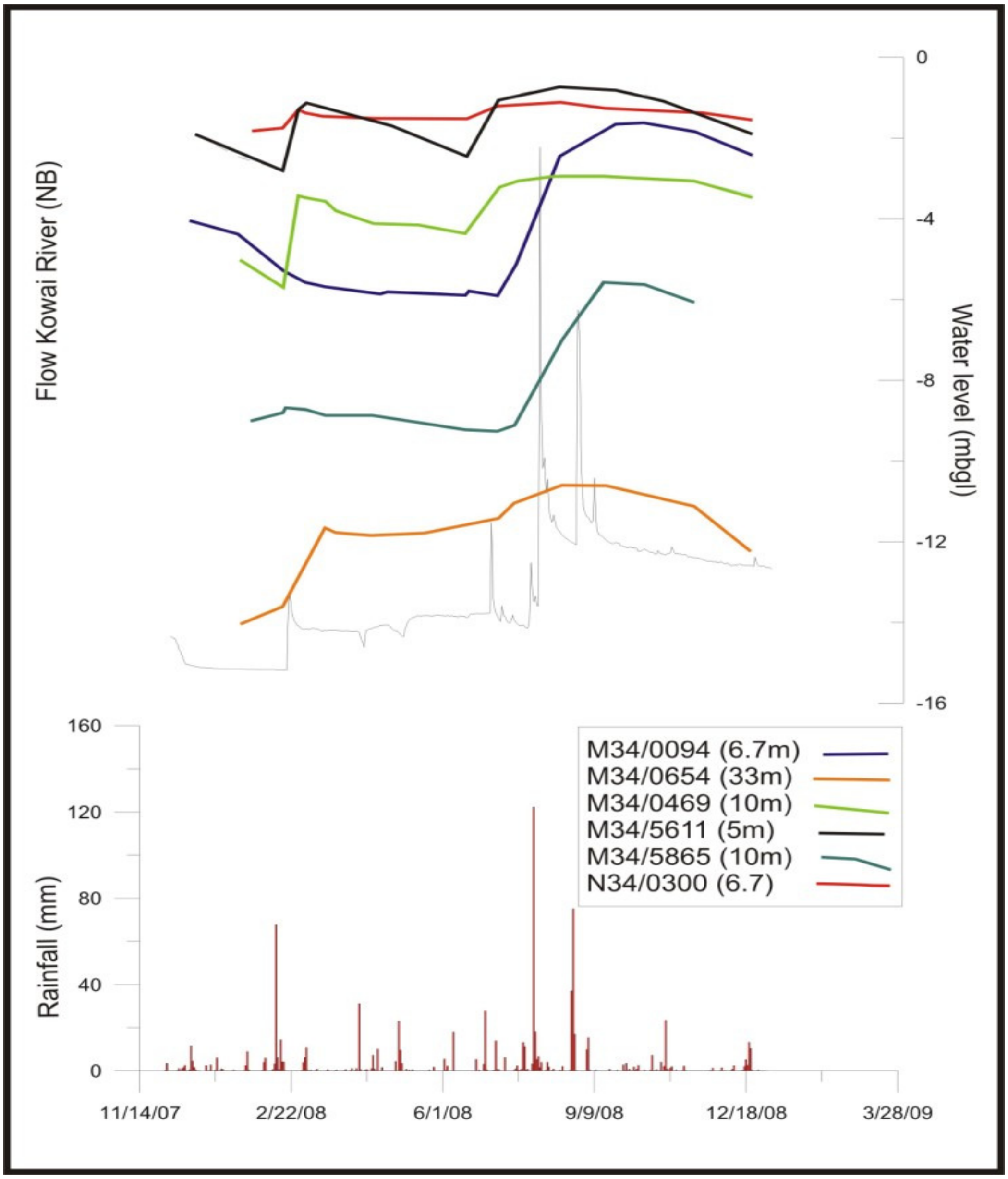

Figure 3.17 Selected water levels from wells located near the Kowai River (NB). Rainfall data is taken from the Met service station at Amberley. Flow data is unprocessed data from the surface water recorder on the Kowai River (NB) at Greys Road. The figure in brackets next to the Site ID is well depth.

Shown in Figure 3.17 are wells that are located near to the Kowai River (NB). Water level curves for M34/5611 and M34/0469 look similar to a river hydrograph, suggesting these wells are hydraulically connected to the river. N34/0300 has a similar but more muted pattern (M34/5611 R^2 0.76 and M34/0469 R^2 0.72, Appendix 3e) due to its increased distance from the river. Water levels in this bore correlate with M34/0444 (44m deep R^2 0.81, located near M34/5611, Appendix 3e). M34/0444 and

N34/0300 are likely to be recharged by the Kowai River and rainfall. M34/0654 water level data appears to respond to changes in flow in the river or rainfall.

M34/0094 and M34/5865 are shallow wells located near the Kowai River (NB) (Figure 3.17). Water level data from these wells have a strong correlation (R^2 0.96, Appendix 3e). The water levels in these wells increased significantly after the major Winter rainfall. Their proximity to the river and water levels suggests that these wells are at least partially recharged from the Kowai River (NB). Interestingly neither of these wells responded significantly to the February 2008 rainfall event or smaller rainfall events. This is likely due to the high ET rates during Summer (Lloyd, 2002).

3.5.2 Waipara zone

Water levels from wells located near Amberley swamp are shown in Figure 3.18. Water levels from most of the wells are fairly similar except M34/0662 (see later discussion). The water levels in all these wells rose following the major Winter rainfall events. Of these wells M34/0095, M34/0662 and M34/0670 are furthest away from the swamp. The water levels in these wells were first to peak and then first to recede. M34/0751 is the closest well to the swamp and its water level did not start to recede until December (see section 3.2.4). This indicates these wells are recharged from rainfall and Southwards flowing groundwater upwelling due to the Broomfield Fault.

Shown in Figure 3.19 are selected shallower wells located in the Waipara Basin. All these wells have a saw tooth pattern, though only M34/0043 is unused. N34/0058 and M34/0754 are irrigation wells and M34/0311 is used frequently for stock water and domestic purposes. Of note is the decline in water levels N34/0058 and M34/0311 between late 1999 to February 2008; -2.5m for N34/0058 and -3.4m for M34/0311. Following the major Winter rainfall events water levels in both wells rose sharply, though not back to the late 1999 level. This drop in water level is likely due to increasing abstraction in the Waipara Basin and successive drier years (2004 – 2006). M34/0311 is likely to be rainfall recharged because it is not located near any surface water sources while N34/0058 may be recharged from the nearby Omihi Stream. M34/0043 is clearly affected by pumping interference and recharged by rainfall.

M34/0754 water level is not declining over time suggesting a continuous recharge source.

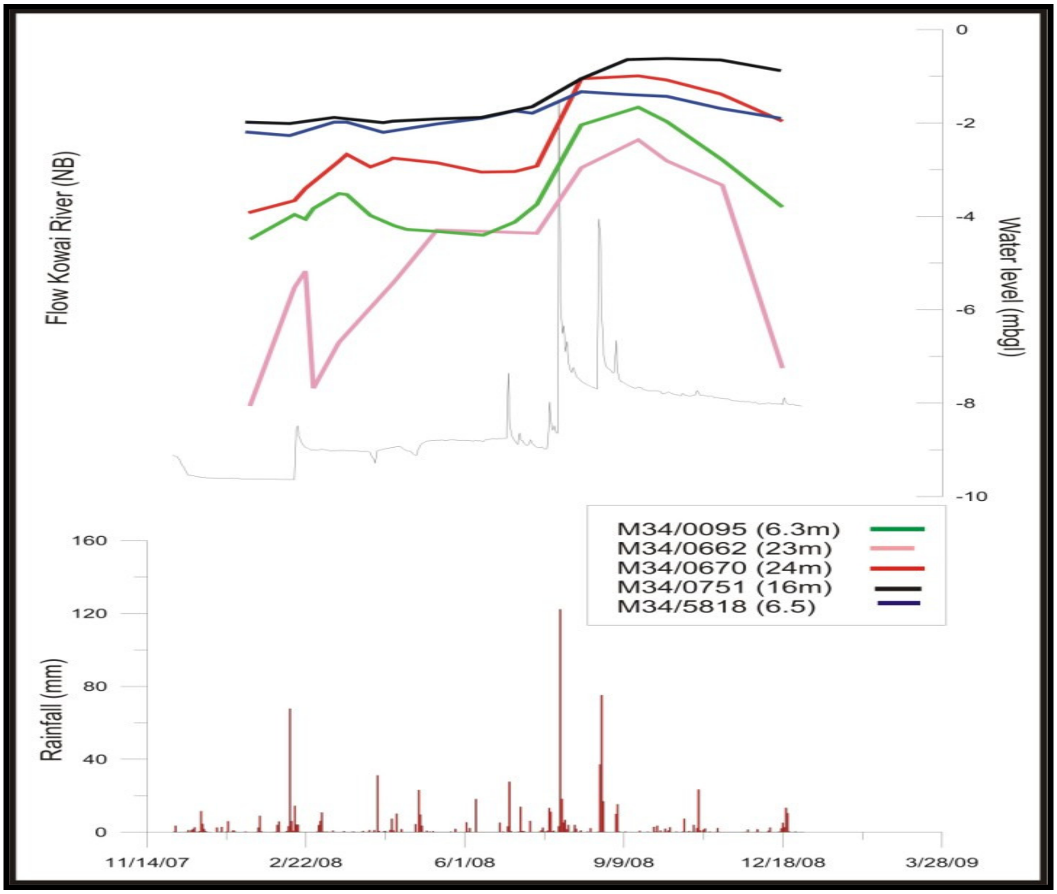

Figure 3.18 Selected water levels from wells located near Amberley Swamp. Rainfall data is taken from the Met service station at Amberley. Flow data is unprocessed data from the surface water recorder on the Kowai River (NB) at Greys Road. The figure in brackets next to the Site ID is well depth.

Figure 3.20 shows a number of deeper wells located in the Waipara Basin plus a deeper well located in the Kowai zone. Water levels in N34/0060 dropped by -3.8m between February 2001 and February 2008 (unused well). The water level in this well rose after the major Winter rainfall event but peaked in December, 2008. M34/0722 is irrigation well and from 2000 to early 2008 the water level in this well declined by -1.5m. Following the Winter rainfall of 2008 this well recorded its highest ever water level. M34/0765 is an unused well located within 200m of M34/0043 (see Figure 3.19). Between 2000 and February 2008 the water level in this well declined by approximately -5.5m. The water level rose after the 2008 Winter rainfall but not to the levels recorded in 2000. Examining the M34/0765 plot shows that the lowest annual levels are typically recorded in Spring and Summer. However since 2006 the recession slope during this period has steepened considerably. N34/0110 has been unused since at least 2005. This well is affected by pumping from neighbouring wells. The water levels in those wells correlate very well with N34/0110 suggesting they are all within a connected system (N34/0134, 145m deep R^2 = 0.80. N34/0142, 155m deep R^2 = 0.96. N34/0143, 120m deep R^2 = 0.86, Appendix 3e). M34/5644 has only a year of water level data. This well has a low yield (<0.1 L/s) and water levels suggest it is not immediately affected by rainfall.

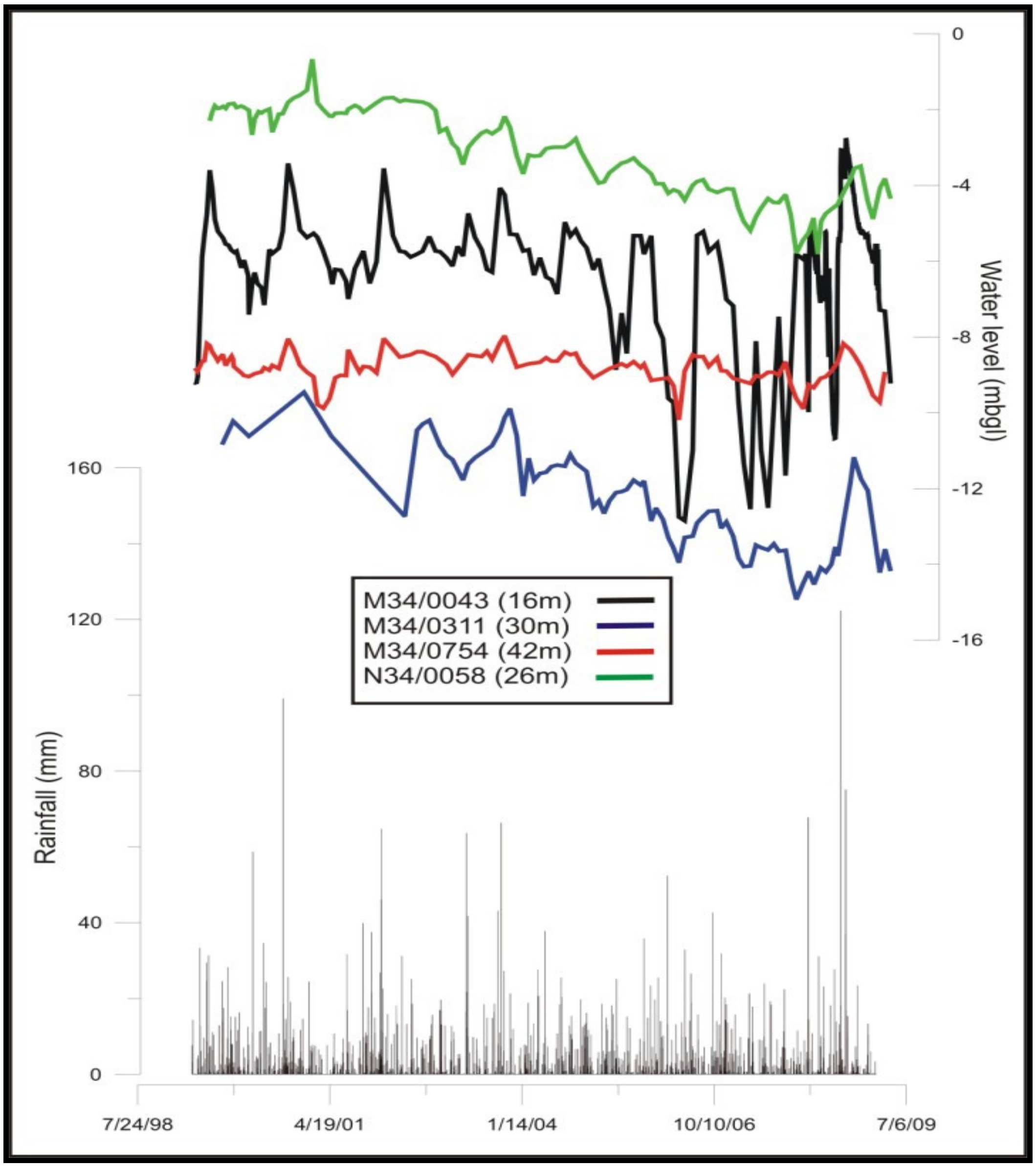

Figure 3.19 Selected water levels from wells located in the Waipara zone. Rainfall data is taken from the Met service station at Amberley. The figure in brackets next to the Site ID is well depth.

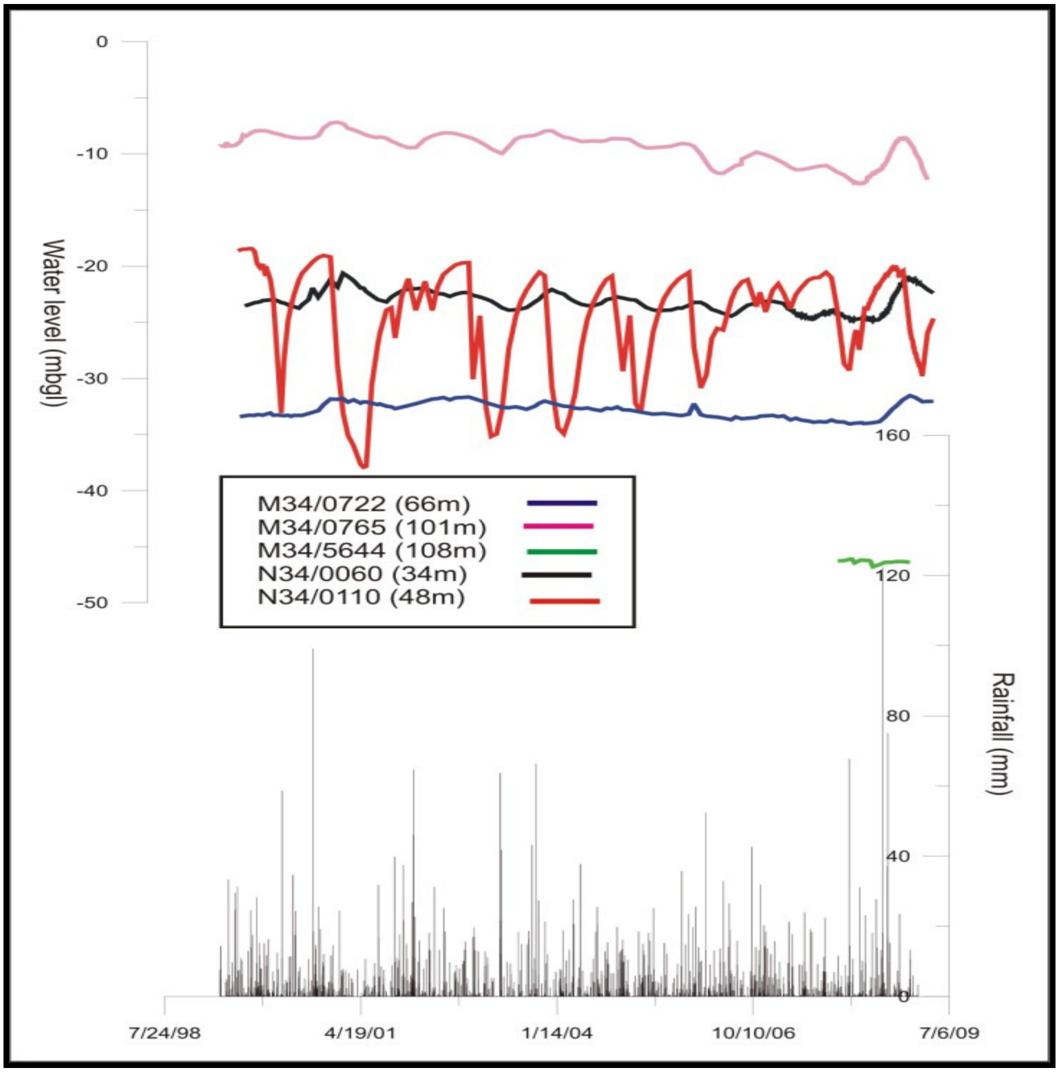

Figure 3.20 Selected water levels from wells located in the Waipara zone and M34/5644 located near Amberley in the Kowai zone. Rainfall data is taken from the Met service station at Amberley. The figure in brackets next to the Site ID is well depth.

3.5.3 Artesian heads

There are a number of artesian wells in the study area (Figure 3.21). Flowing artesian heads are assumed to be related to water pressurised between confining layers. Figure 3.21 shows the locations of wells in the study area with measured/ observed positive heads (greater than >0.1m above GL).

Most of the artesian wells occur in the Saltwater Creek area and along the coastal strip between Amberley Beach and Saltwater Creek. There are likely to be more artesian wells in these areas than are shown in Figure 3.21. From section 2.2.2 it was proposed that the geology of Saltwater Creek and the coastal strip was composed of intercalated marine/ marginal marine and terrestrial sediments, similar to the Kaiapoi and Christchurch artesian system (Talbot et al, 1986. Taylor et al, 1989. Lovell, 1998). The presence of flowing artesian wells supports this hypothesis. Heads in this region are generally in the order of +0.1m - +25m.

Within the Waipara Basin there are a number of flowing artesian wells located along the margins of the basin. It is interpreted that these wells are located in interbedded alluvial fans and fluvial sediments (reference section 2.5.2). N34/0131, N34/0139 and M34/5573 have heads greater than 4m above GL up to 30m above GL. N34/0106 (68m deep) has water levels in the range of +1m above GL to -3.70 mbgl whereas N34/0107 (28m deep) has water levels in the range of -2.25 mbgl – 4m above GL. Dravid and Brown (1997) suggested that decreasing heads with depth in the Hawkes Bay are the result of a hydraulically interconnected system with a common recharge zone. Alternatively bore logs from N34/0106 and N34/0107 suggest the shallow bore is screened in a thin gravel layer wedged between two clay beds whereas N34/0106 is screened in “free gravel” intercalated with sandy gravels with traces of clay.

M34/0753 and M34/0726 are located in the centre of the basin. M34/0753 (29m deep) went flowing artesian once in September 2000, after significant rainfall had fell. The water level in this bore is usually quite high (>-2mbgl). There are no obvious confining layers in the bore log. M34/0726 (total depth 114m, pulled back and screened at 64 – 68m & 72m) water level ranges from +0.3 – 6.8 m above GL. The bore log shows numerous confining layers between 48 – 64, 70 and 73 – 83 mbgl. Below this level limestone clasts are recorded in the borelog. These layers are likely to be related to fluvial low energy environments or to the Waipara Downs fan system (see section 2.2.10 and 2.2.11).

Figure 3.21 Map showing the spatial distribution of wells that have at least one flowing artesian head measured or observed and recorded on Environment Canterbury's wells database.

3.6 Chapter summary

The weather over the study period went from extremely dry in Summer to very wet in Winter. There were three major rainfall events in 2008 which accounted for 50% of the annual total at the Amberley Met service station.

Characterisation of losses and gains from major rivers and stream was attempted. Generally, most of the rivers/streams lost significant amounts of water in their lower reaches, except the Omihi Stream which gained significantly in its lower reaches. The Waipara River as it crosses the Waipara Basin has a complex flow regime but it is considered not to be a significant recharge source to the basin. It was shown that the Amberley swamp can act as surface water storage with limited outflow supplementing the flow of the Kowai River (NB).

Springs have proved to be reliable indicators of local groundwater flow directions. Furthermore they have shown clearly that the Mount Brown Formation is an aquifer providing base flow to the Kowai River (NB).

Aquifer test data provides an estimate of the hydraulic proprieties of the sediments in the Waipara Basin which showed that generally the transmissivities are quite low. The results of aquifer tests conducted in the Waipara Basin were examined showing there was a complex pattern of leakage and potential for pumping interference.

Water level data from the study area was also examined to indicate recharge and responsiveness. Generally the Saltwater Creek area seems to be recharged from the Ashley River; the Downlands receives recharge from rainfall and local streams. Water levels from some shallow wells in the Waipara Basin show significant pumping interference effects and an overall declining trend.

4 Chapter four: Groundwater chemistry

4.1 Introduction

Chemical techniques have been used successfully on the Canterbury Plains to identify recharge sources (Haywood, 2002. Vincent, 2005. Dommisse, 2006). Workers have shown relationships between the concentration of determinants in groundwater (i.e. Chloride and Nitrate Nitrogen) and recharge sources flowing through predominantly Torlesse derived gravels (Haywood, 2002). Other studies have used chemical ratios to determine recharge and saltwater intrusion (Hertel, 1998).

Groundwater chemistry has been used here primarily to identify recharge. However, it became apparent during the course of the study that the groundwater chemistry could be also used to define Hydrochemical zones. These Hydrochemical zones are delineated on the basis of the sediments in which they flow, the composition of the recharging water and land use influences. Furthermore, as there is limited whole rock chemistry data for the sediments in the area, water chemistry data is used to infer information about the minerals within the sediments.

4.2 Data and methods

There is a sizeable amount of chemical data acquired from surface water and groundwater sites in the study area. These data have been collected for a variety of reasons, over a significant period of time (>40 years), collected in different manners and analysed using various analytical methods (Appendix 4a & 4b). An attempt has been made to make use of this data set.

A point to note about this data set is for the most part the wells from which the water was collected for the chemical analysis are privately owned and are predominantly used for domestic, stock water and irrigational purposes. As such, the wells are presumably located in optimal sites for their intended purpose. It is assumed that a large numbers of wells will provide appropriate and representative chemical information (i.e. buckshot method).

The chemical data has been arranged into median concentrations for each determinant per site. Medians were used because they are less sensitive to extreme values

(Daughney and Reeves, 2003). Analyses were omitted from the median calculations if they had not analysed for all the major ions (though in some cases Sulphate concentrations have been estimated), and if the ion balance is greater than ±10%. Ion balances with an error of less than ±10% indicate that all the important chemical determinants have been sampled for and that there have not been significant analytical errors. Abraham and Hansen (2004) suggest that ±10% is appropriate threshold for the plains as many of the wells and streams have low ionic loads. Minor and trace elements are not always determined due to financial constraints. Median values were calculated for only analyses that fitted the criteria stated above. Therefore the median values of the minor and trace elements are often based on a fewer number of total sample analyses than the median concentrations calculated for the major ions. It should be noted that the vast majority of the wells sampled have only been sampled once (Appendix 4b). For non-detections a value of half the detection limit was used (Haywood, 2002).

A simplifying assumption of data presented as median per site is that the chemistry of the groundwater does not change significantly with time. Haywood (2002) and Vincent (2005) show that seasonal trends in Chloride, Sulphate and Nitrate-Nitrogen are common. It has been noted that after significant snowfall events Nitrate-Nitrogen can significantly increase (C Hanson per com. 2006). Figure 4.1 shows Chloride data from wells, located within the study area, that were sampled annually or quarterly by Environment Canterbury. Wells M34/0353 and M34/0223 both show increases in Chloride following the significant winter rainfall that fell in the winter of 2008. M34/0758 shows no apparent trend at this scale. N34/0062 is located within 300m from the coast and there is an increase in Chloride concentration till about 2000 after which it flattens off (Figure 4.1). This well has been identified as being susceptible to saltwater intrusion (Aitchison-Earl et al, 2003).

However, given that the major controls on the chemistry of these waters are likely to be governed by water rock interactions, the composition of the recharging water, and land use, it is therefore considered that the simplifying assumption of no significant variation in chemical composition over the time scale considered is valid.

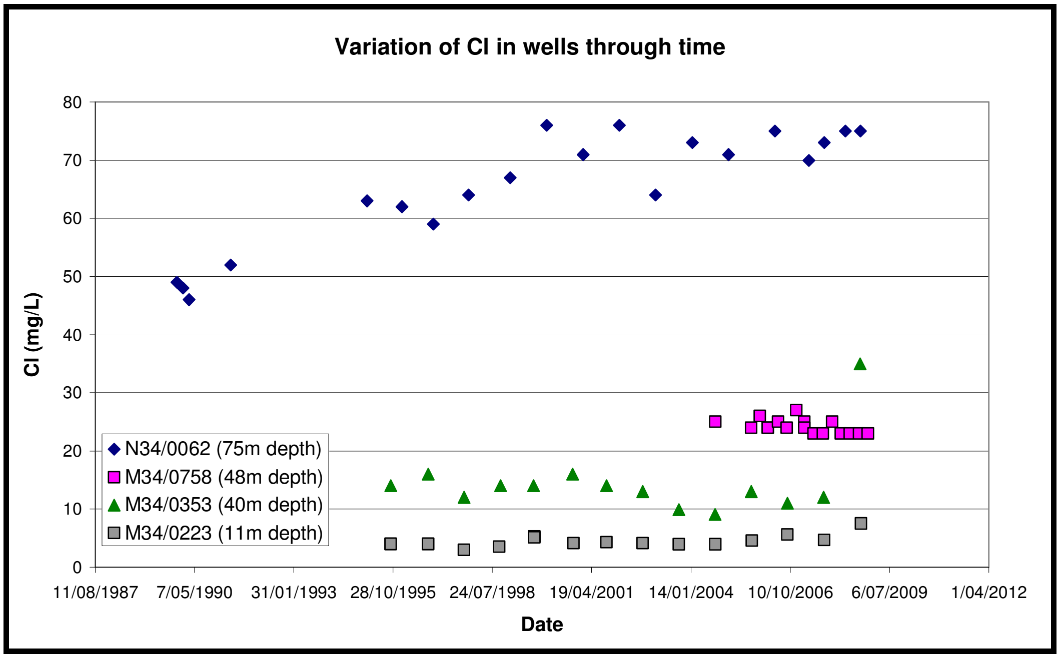

Figure 4.1 Chloride data from selected wells sampled annually or quarterly by Environment Canterbury.

The median data was analysed in three ways. The first method was to define "zones" on the basis of visual inspection of the wells and springs chemistry results (hereafter referred to as chemical zonation analysis). The data from each zone was then tabulated and box & whisker plots were constructed to test the significance of the zonation. The box and whisker plots were constructed in Excel using 5, 25, median, 75 and 95 percentiles. Outliers (>95 percentile) are not shown on the plots (Appendix 4c). The second method used was hierarchical cluster analysis (HCA) in STATISTICA 6.0 © using the methodology of Daughney and Reeves (2003). Eight determinants were used (Calcium, Magnesium, Chloride, Bicarbonate, Nitrate Nitrogen, Potassium, Sulphate and Sodium) after being logarithmically transformed so as to conform to the assumptions of normal distribution and equal variance. Rivers and wells without Nitrate Nitrogen data were excluded from the analysis (Appendix 4d). The third method of looking at the median data was to construct Piper diagrams (Appendix 4e).

4.2.1 Redox states

An attempt has been made to classify the median groundwater chemical results in terms of anoxic or oxidised conditions. This Redox classification will be later used to infer information about flow paths and the sediments in which the groundwater has flowed.

Most of the data on the Squalarc[5] database has been analysed and results reported in dissolved or total concentrations (Appendix 4b). However total or dissolved concentration can include both reduced and oxidised species of that determinant. Therefore a set of qualitative criteria were used to classify the redox state of the water (per com. C Hansen and P Abraham 2008. Table 4.1). Care has been taken when using these criteria as the presence or absence of these determinants may not necessarily be related to redox conditions e.g. it may simply be that there is no soluble source of a determinant up gradient of that site.

Table 4.1 Criteria used in this study to define Reduced and Oxidised Groundwater. NB the Dissolved oxygen threshold concentration is based on empirical evidence from this study and from an average estimate of the upper DO limit for denitrification from Gillham and Cherry ((1978) as sited in Korom, 1992).

Reduced Groundwater conditions	Oxidised Groundwater conditions
Dissolved oxygen concentrations <2 mg/L	Dissolved oxygen concentrations >2 mg/L
Low to nil Nitrate Nitrogen	Relatively high Nitrate Nitrogen concentrations
Low to nil Sulphate	Relatively high Sulphate concentration
H_2S odour detected	Odourless
Ammonia Nitrogen often present	Low to nil Ammonia Nitrogen
Iron often present	Low to nil Iron
Manganese often present	Low to nil Manganese
Arsenic occasional present	Low to nil Arsenic

Significant weight was given to the detection of H_2S odour as this is indicator of Sulphate reduction (Rosen, 2001). However it is acknowledged that sample odours may not always be detected. This may be due to weather conditions at the time of sampling (windy), inattention etc. There are instances where the DO concentrations are greater than >2 mg/L but H2S has been detected. In these instances the well has been given labelled “C” for complex (n=2, Appendix 4b).

Once classified, box and whisker plots were constructed to test if there were significant differences in determinant concentrations between classes. A significant difference was inferred when there was no over lap of the boxes (25 to 75 percentiles) between the different classes.

[5] Squalarc is the name of Environment Canterbury’s water quality database.

4.2.2 Sampling programme

For this project 37 wells and six surface water sites were sampled in October 2008. The wells that were sampled were selected on the basis of their depth and geographic location. The surface water sites and springs are sites that were sampled weekly for oxygen and hydrogen stable isotopes.

Appendix 4a shows what individual samples were analysed for, what analytical methods were used and the analytical detection limits. Budgetary constraints meant that not all surface water sites were sampled for the same determinants as the groundwater sites, while some determinants that median concentration was calculated for were not sampled for in this study (Appendix 4a).

Every attempt was made to collect the samples in accordance with Environment Canterbury procedures (ECan, 1999). Before sampling from a well it was purged so that at least three times the volume of water in the casing was pumped out to ensure a representative sample. pH, conductivity and water temperature was monitored on field meters to ensure the well had been sufficiently purged (Daughney et al, 2007). Samples were taken from a point closest to the wellhead. An attempt was made to take DO readings at every site however the quality of this data is affected by the set up of the pump on the well and sampling point. In some situations the sample can become aerated and as such DO readings were not recorded.

Table 4.2 Results from chemical analysis of wells collected for this study.

Site_ID	Date	Alkalinity to 4.5 mg HCO3/L	Ammonia Nitrogen mg/L	As diss. mg/L	Br mg/L	Ca diss. mg/L	Cl mg/L	DRP mg/L	F mg/L	Fe diss. mg/L	Mg diss. mg/L	Mn diss. mg/L	Nitrate Nitrogen mg/L	K diss. mg/L	Na diss. mg/L	SO_4 mg/L	Total Hardness mg CaCO3/L	pH field FIELD	DO mg/L FIELD	DO sat. % FIELD	Cond. mS/m FIELD	Water Temp ℃ FIELD	TDS	Ion balance
M34/0009	12-Oct-08	95	0.01	<0.002	0.21	28	64	<0.001	<0.2	0.81	7.2	0.25	<0.1	1.9	40	7.7	100	6.2	0.17	1.6	42.8	13	149	4
M34/0334	13-Oct-08	35	0.01	<0.002	<0.05	11	4.7	0.011	<0.2	<0.03	2	<0.01	0.6	1	5.7	5.1	36	6.8	6.16	59.2	10.1	13.2	30	7.2
M34/0444	13-Oct-08	180	<0.005	<0.002	0.17	43	56	0.013	0.2	0.85	11	0.02	<0.1	1.6	47	8.3	153	6.8	0.04	0.4	54.4	13.2	167	4.6
M34/0497	17-Oct-08	113	0.045	<0.002	0.06	30	32	<0.001	<0.2	3.2	7.6	0.32	3.8	2	27	27	106	6.4	2.5	23.6	41.8	12.6	126	-1.6
M34/0614	14-Oct-08	121	0.008	<0.002	0.12	30	11	0.008	<0.2	0.18	3.9	0.38	0.1	<0.1	20	5.6	91	6.8	0.06	0.6	26.9	14.6	71	5.7
M34/0647	22-Oct-08	161	0.045	<0.002	0.27	33	39	0.016	<0.2	0.36	9.5	0.44	<0.1	1.6	33	4.8	122	7	12	0.5	45.1	12.7	121	1.3
M34/0661	14-Oct-08	180	0.063	<0.002	0.15	36	9.5	0.084	<0.2	0.22	6.6	0.19	<0.1	1.5	33	2.8	117	7.1	0.05	0.5	36.2	13	89	7.5
M34/0670	12-Oct-08	76	0.055	<0.002	<0.05	22	16	0.003	<0.2	0.27	5.3	0.04	8.1	<0.1	27	14	77	7.8	2.9	29.3	29.6	15.7	84	3
M34/0703	12-Oct-08	38	0.019	<0.002	<0.05	9.5	4.5	<0.001	<0.2	0.56	2.1	0.2	0.1	1.1	6.6	4.6	32	6.5	1.46	13.9	10.1	12.9	28	7.5
M34/0732	13-Oct-08	195	<0.005	<0.002	0.17	31	24	0.003	<0.2	1.5	12	0.33	<0.1	1.5	47	4.9	127	7.2	0.04	0.4	44.8	13.3	120	8.2
M34/0751	12-Oct-08	138	0.008	<0.002	<0.05	34	13	<0.001	<0.2	0.75	6.6	0.4	<0.1	1.3	20	4.1	112	7	0.6	5.7	30.8	12.7	79	8
M34/0772	14-Oct-08	120	0.015	<0.002	0.46	50	65	0.013	<0.2	0.03	7.8	<0.01	0.7	1.6	27	15	157	7.3	0.29	2.8	47.7	13.3	166	2.2
M34/0791	20-Oct-08	53	<0.005	<0.002	0.09	10	14	0.005	0.2	0.47	2.6	0.09	2	1	16	4.2	36	7.1	0.39	3.4	16.8	13.6	48	-1.7
M34/0798	13-Oct-08	276	0.16	0.002	0.62	45	130	0.022	0.5	3.7	15	0.52	0.1	2.8	130	11	174	7	NR	NR	94.1	13.4	334	5.1
M34/5561	12-Oct-08	183	2.2	<0.002	0.16	18	40	<0.001	0.3	16	7.4	0.83	<0.1	2.1	59	0.4	75	7.6	0.07	0.7	52.1	13.7	127	8.1
M34/5573	14-Oct-08	278	0.036	<0.002	<0.05	82	19	0.002	<0.2	0.05	14	<0.01	1.2	2	23	28	262	7.3	NR	NR	62.1	14.8	168	4.5
M34/5574	14-Oct-08	144	0.019	<0.002	0.23	45	19	0.01	<0.2	0.05	7.1	0.01	1	1.7	22	14	142	7.3	2.89	26.2	34.9	13.6	109	8.1
M34/5575	13-Oct-08	197	0.051	<0.002	0.49	58	89	0.034	<0.2	0.08	15	0.51	<0.1	1.9	51	17	207	7.1	0.41	4	70	13.3	232	2.6
M34/5604	13-Oct-08	134	0.015	<0.002	0.2	15	34	0.072	0.6	0.65	7.4	0.31	<0.1	1.1	54	7.2	68	7	NR	NR	38.3	13	119	6.1
M34/5611	13-Oct-08	38	0.012	<0.002	<0.05	15	27	0.007	<0.2	0.25	3.9	0.08	1.1	1.7	17	10	54	5.8	0.26	2.4	20.7	10.7	75	5.5
M34/5624	20-Oct-08	114	<0.005	<0.002	<0.05	22	12	0.02	0.2	0.09	4.1	<0.01	0.2	2.3	22	8.1	72	7.4	0.06	0.6	24.4	13.4	71	1.1
M34/5627	13-Oct-08	42	0.023	<0.002	<0.05	13	5	0.006	<0.2	<0.03	2.3	<0.01	0.5	1.1	6.8	5.4	42	6.9	8.79	84.5	11.6	13.2	34	8.7
M34/5639	14-Oct-08	68	0.018	<0.002	0.09	18	12	0.01	<0.2	0.03	3.5	0.02	1.1	1.1	16	3.7	59	7.1	0.15	1.5	18.6	12.4	54	8.6
M34/5689	13-Oct-08	74	0.016	<0.002	0.17	29	49	0.005	<0.2	<0.03	5	0.22	5	1.4	33	3.3	93	6.5	NR	NR	34.5	12.9	121	5
M34/5818	12-Oct-08	131	<0.005	<0.002	0.06	28	23	0.025	<0.2	0.07	5.3	0.13	<0.1	1.4	35	6.6	92	7	0.77	7.3	33.9	12.9	99	7.3
M34/5865	12-Oct-08	234	0.009	<0.002	<0.05	92	23	0.05	<0.2	0.04	3.4	<0.01	7.3	2.5	16	11	244	7.2	4.62	44.6	59.4	13.4	148	3.7
M35/5987	13-Oct-08	169	<0.005	<0.002	0.1	24	28	0.001	<0.2	0.88	12	0.65	0.1	1.7	45	5.1	109	6.8	0.54	5.2	41.5	13.3	116	7.2
N33/0064	16-Oct-08	123	<0.005	<0.002	0.34	48	43	0.22	0.2	<0.03	9.5	<0.01	3.6	1.8	42	40	159	6.3	2.81	26.5	50.1	12.3	184	7.7
N34/0058	14-Oct-08	376	0.1	<0.002	1	140	96	0.019	0.2	0.48	18	0.86	<0.1	3.1	62	54	424	6.9	0.16	1.6	116.2	13.9	373	6.1
N34/0059	16-Oct-08	188	0.017	<0.002	0.94	96	190	0.004	<0.2	0.04	17	<0.01	4.9	2.5	77	33	310	7.4	NR	NR	109.3	13.9	416	0.7
N34/0060	17-Oct-08	192	<0.005	<0.002	0.34	66	26	0.016	<0.2	0.06	8.8	0.02	1	3.3	38	51	201	7.1	4.7	45.5	57.7	13.5	193	6.9
N34/0097	17-Oct-08	237	<0.005	<0.002	0.35	89	36	0.04	<0.2	<0.03	9.6	<0.01	4.1	2.7	27	37	262	7.1	3.43	32.9	65.5	13	201	4.1
N34/0129	12-Oct-08	188	<0.005	<0.002	0.84	74	190	0.02	<0.2	0.09	15	0.01	0.9	2.9	100	29	247	7.2	5.89	55	107.3	13.5	411	1.3
N34/0132	16-Oct-08	313	0.26	<0.002	0.39	90	36	0.031	<0.2	0.16	16	0.04	0.1	13	33	32	291	7	0.09	0.9	73.3	13.3	220	5.4
N34/0143	16-Oct-08	288	0.013	<0.002	0.42	100	56	0.016	0.2	0.41	9.3	0.02	0.1	3.1	43	46	288	7.1	NR	NR	79.2	15.1	257	3

Table 4.3 Results from chemical analysis of surface water sites collected for this study.

Site_ID	Date	Alkalinity to pH 4,5 mg HCO3/L	Ammonia Nitrogen mg/L	As diss. mg/L		Ca diss. mg/L	Cl mg/L	DRP mg/L	F mg/L	Fe diss. mg/L	Mg diss. mg/L	Mn diss. mg/L	Nitrate Nitrogen mg/L	K diss. mg/L	Na diss. mg/L	SO_4 mg/L	Total Hardness mg CaCO3/L	pH field FIELD	DO mg/L FIELD	Do sat. % FIELD	Cond. mS/m FIELD	Water Temp. ℃ FIELD	TDS	Ion balance
SQ30182	15-Oct-08	36	0.005	<0.002		11	2.6	<0.001	<0.2	0.03	1.9	<0.01	0.2	1	5.3	4.7	35	7.1	9.82	95.7	9	13.8	27	10.8
SQ33962	15-Oct-08	85	<0.005	<0.002		29	8.2	<0.001	<0.2	0.03	4.6	<0.01	<0.1	1.3	14	25	91	8.5	10.02	101.2	23.9	15.6	82	7
SQ35352	15-Oct-08	150	<0.005	<0.002		48	7.6	<0.001	<0.2	0.03	3	<0.01	0.2	1.1	8.9	9.5	132	8.5	13.61	128.2	31.4	12.4	78	2.9
SQ35353	15-Oct-08	49	0.056	<0.002		23	24	0.008	<0.2	0.16	5.3	<0.01	6.3	2.6	24	24	79	8	8.01	84.2	28.4	17.9	103	5.3
SQ35354	15-Oct-08	33	0.01	<0.002		20	73	0.056	<0.2	0.2	11	0.02	5.8	7.7	43	39	95	5.7	4.42	40.8	46	11.9	194	2
SQ35397	15-Oct-08	246	0.006	<0.002		84	65	0.026	0.2	0.04	14	0.02	1.2	3	49	58	267	7.5	9.94	96.5	73.8	13.8	273	2.6

Above Aesthetic guideline values | Above Health Maximum acceptable value

Values taken from New Zealand Drinking Water Standards (DWSNZ) 2005

NOTES; TDS = Total dissolved solids (calculated by summing the major ions). Diss. = Dissolved. NR = Not recorded. FIELD = data obtained using a field meter.

Site No: SQ30182 Ashley River below Okuku confl, Site No: SQ33962 Waipara River at Laidmore Rd, Site No: SQ35352 Kowai River (North Branch) Onepunga Road, Site No: SQ35353 Spring M34/5521 Bellbird Spring, Site No: SQ35354 Spring M34/5821 Pascoe spring, Site No: SQ35397 Omihi stream Ellis property, Mt Cass Road

4.3 Results

The results of the groundwater and surface water sampling from this study are shown in Table 4.2 and Table 4.3. The median groundwater and spring chemical results are listed in Appendix 4b. Note that there are two wells within the median dataset that are not located in the study area, M35/0444 and M35/0474 (located in the Ashley zone). These two wells are flowing artesian wells located in Waikuku Township and which are recharged by the Ashley River (Sanders, 1997). The water chemistry from these wells reflects river recharge and they have been used as a "model" for Ashley River recharge water.

4.3.1 Chemical zonation

When total dissolved solids (TDS) and other determinants are plotted on a map, areas with similar concentrations become apparent (Figure 4.2). This spatial clustering of well and spring chemistry suggests that the study area can be divided into chemical zones; which will be referred to as Saltwater Creek, Downlands, South Waipara and North Waipara.

Table 4.4 List of determinants that are significantly different between zones. ,

	Saltwater Creek	**Downlands**	**North**	**South**
Saltwater Creek (n=9)				
Downlands (n=39)	HCO3, Br, Ca, Cl, Mg, Mn, K, Reactive SiO2, SO4,Hardness, Cond., TDS			
North (n=25)	HCO3, Br, Ca, Cl, DRP, Mg, K, Reactive SiO2, Na, SO4, pH, Cond., Water temp., TDS	Ca, SO4		
South (n=28)	HCO3, Br, Ca, Cl, Mg, Reactive SiO2, Na, SO4, Hardness, Cond., TDS	Cl, Reactive SiO2, Na, Cond., TDS	HCO3, Br, Ca, Cl, SO4, Hardness, Cond., TDS	

Figure 4.2 Plot of Total dissolved solids (TDS) using median figures for wells, springs and surface water sites (not distinguished on the figure). NB not all sites shown were used in the chemical zonation analysis.

The results of the box and whisker analysis conducted on these zones are schematically illustrated in Table 4.4 and shown in Appendix 4c. For the analysis a statistical difference was inferred when there was no overlap of the box (25 to 75 percentiles) between zones. These differences are listed in Table 4.4. From Table 4.4 we can see that Saltwater Creek is chemically distinct from all other zones. There are a number of differences in determinant concentration between North & South Waipara and South Waipara & Downlands. Except for Calcium and Sulphate, North Waipara and Downlands are similar. From the box and whisker plots in Appendix 4c it can be seen that generally the Downlands and North Waipara have the greatest variability as defined by the length between the whiskers (95 – 5 percentile) and interquartile range.

4.3.2 Hierarchical cluster analysis

The dendrogram and averages of the defined groups derived from the Hierarchical Cluster Analysis (HCA) are shown in Figure 4.3, Table 4.5 and Appendix 4d. Three groups are apparent which were further subdivided to give a total of six subgroups. The groups are named with the first number indicating the group and with the decimal indicating the subgroup (Table 4.5).

Table 4.5 Averages for groups defined by HCA for determinants used in the analysis. Groups are ordered by overall ranking, ranked from highest to lowest concentrations. Depth and TDS were not included in the HCA but shown for reference.

Groups/ subgroups	Depth	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3-N	TDS
	mbgl	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
3.2	-39	58.3	19.9	70.2	5.7	162.7	132.2	41.2	8.04	490
2.1	-44	76.6	13.3	63.2	3.7	262.8	96.6	30.7	0.11	547
3.3	-47	55.1	7.8	31.2	2.2	187.4	34.4	24.0	2.07	342
2.2	-52	24.1	6.2	31.6	1.4	142.6	21.6	5.3	0.11	233
3.1	-25	14.4	5.3	27.1	2.2	51.6	33.3	11.2	4.05	145
1.0	-20	10.2	2.3	5.8	1.0	42.7	4.6	5.4	0.32	72

From Table 4.5 we can see that group 1.0 has the lowest average ionic loads and are generally quite shallow. Subgroup 2.1 has the highest average concentrations of TDS, bicarbonate and calcium, and relative high concentrations of all other determinants except Nitrate Nitrogen. Average determinant concentrations from Subroup 2.2 are in the midrange except Nitrate Nitrogen which only just above the detection limit. All of the subgroups in group 3 have elevated average Nitrate Nitrogen concentrations when compared to the other groups. Group 3 also has the highest average concentrations of Potassium except when compared to subgroup 2.1. Subgroup 3.2 has the highest average values of most of the determinants, whereas subgroup 3.3 has midrange values for most of the determinants and subgroup 3.1 has relatively low concentrations for all the determinants.

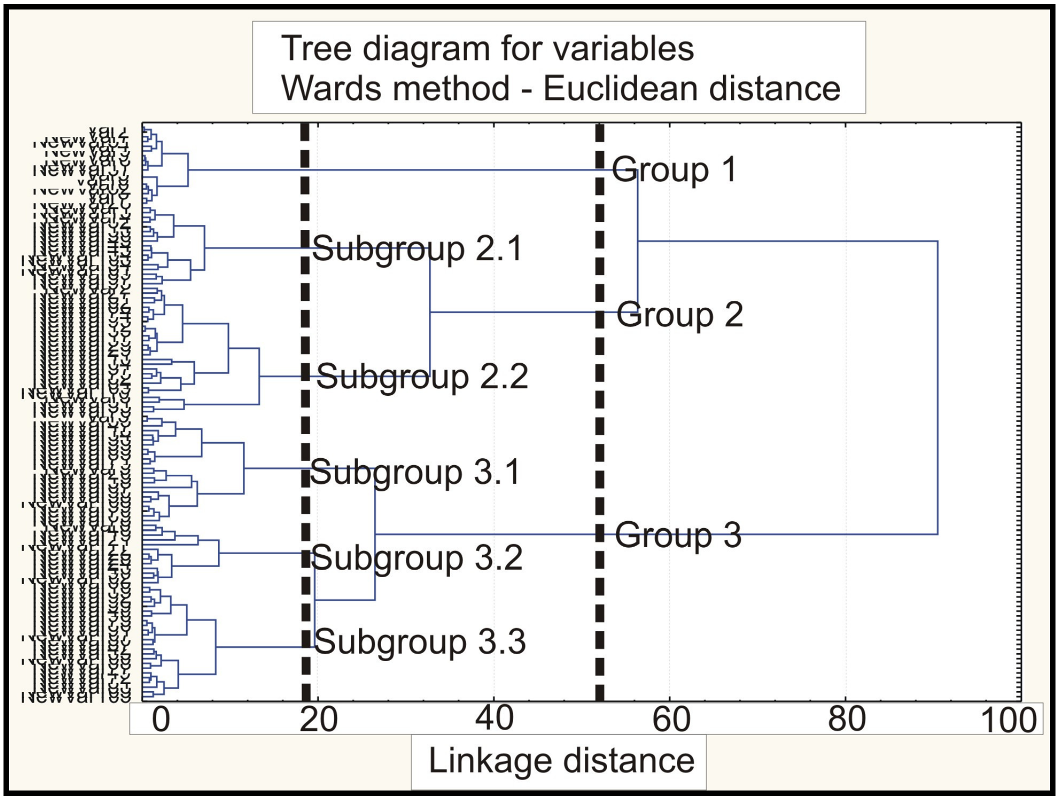

Figure 4.3 Dendrogram produced from the Hierarchical Cluster Analysis. Dashed black lines denote group thresholds defined by the author. The vertical scale has 121 sites shown though not very well.

4.3.3 Piper plots

Figure 4.4 is a Piper diagram plotting all the sites with median data by groundwater zone. Piper diagrams for the individual zones are shown in Appendix.4e

Sites from Saltwater Creek zone are *Calcium – Bicarbonate type* plotting as a relatively tight group. There is a two outlier in the Saltwater Creek zone group which plots in the as *Sodium or Potassium type* (Fetter, 2001). Sites in the North Waipara zone predominately plot in as *Calcium – Bicarbonate type* with a small number plotting within the *no dominant type* to *Sodium or Potassium type*. For South Waipara zone most sites plot as *no dominant type* with some in the *Calcium – Bicarbonate type*. In the Downlands zone most sites plot in the *Sodium or Potassium type* zone.

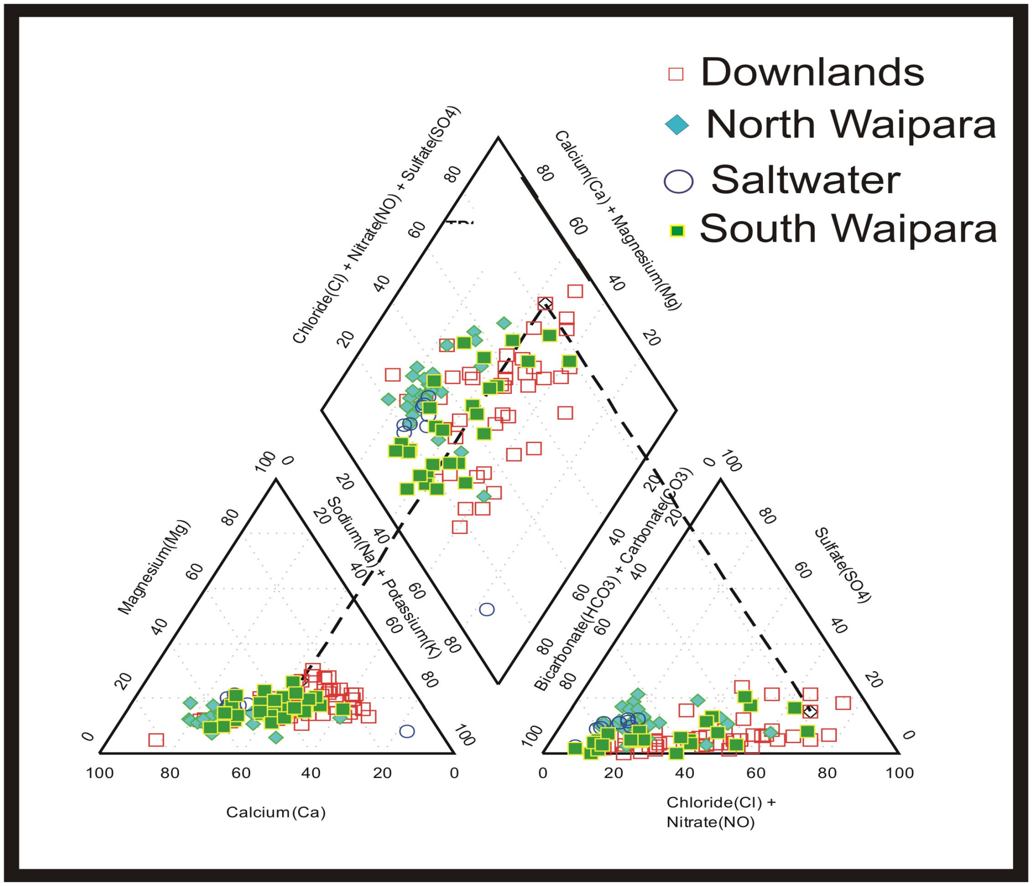

Figure 4.4 Piper plot of median concentration (mg/L) from wells, springs and surface water sites. Sites are grouped on chemical zones. Dashed black line is indicating the location of a single sample in the three triangles/ diamond.

4.3.4 Comparison to the New Zealand Drinking water standards

In Table 4.2, Table 4.3 and Appendix 4b results exceeding the 2005 New Zealand Drinking Water Standards (DWSNZ, 2005) have been highlighted. Table 4.6 lists the transgression by determinant for the median data.

From Table 4.6 we can see that nearly half of the sites in the dataset exceed the limits set for Iron and Manganese. These sites are typically wells and springs and often both determinants exceed the standards at the same site. Transgressions of total hardness and pH are common, though rarely simultaneously at the same site. Nitrate Nitrogen concentrations above the maximum acceptable value occur in a small number of shallow wells. However a tenth of the sites in the in the dataset have Nitrate Nitrogen concentration greater than 5.7 mg/L. This reflects land use influence and the dominance of shallow wells in the dataset (Figure 4.5).

Table 4.6 Transgression limits and sum of sites (using median data) that exceed those limits. Only shown are determinants that have exceeded the trangression limits. Transgsssion limits taken from the New Zealand drinking water standard (DWSNZ, 2005). Total number of wells and springs in dataset = 124. GV = guideline value. MAV = Maximum acceptable value.

Determinand	Aesthetic GV	Health MAV	Exceeding Aesthetic GV Count	Exceeding Health MAV Count	Exceeding ½ Health MAV Count
Ammonia Nitrogen	1.2 mg/L	N/A	5 (4%)		
Arsenic	N/A	0.01 mg/L		4 (2%)	
Iron	0.2 mg/L	N/A	45 (36%)		
Manganese	0.04 mg/L	0.4 mg/L	33 (26%)	22 (17%)	
Nitrate Nitrogen	N/A	11.3 mg/L ½ MAV = ≥5.7 mg/L		4 (3%)	11 (9%)
Chloride	250 mg/L	N/A	1 (1%)		
Total Hardness	200 $CaCO_3$ mg/L	N/A	36 (29%)		
Total dissolved solids	1000 mg/L	N/A	1 (1%)		
pH (Chem)	7.0 – 8.5	N/A	29 (23%)		
pH (field)	7.0 – 8.5	N/A	35 (28%)		

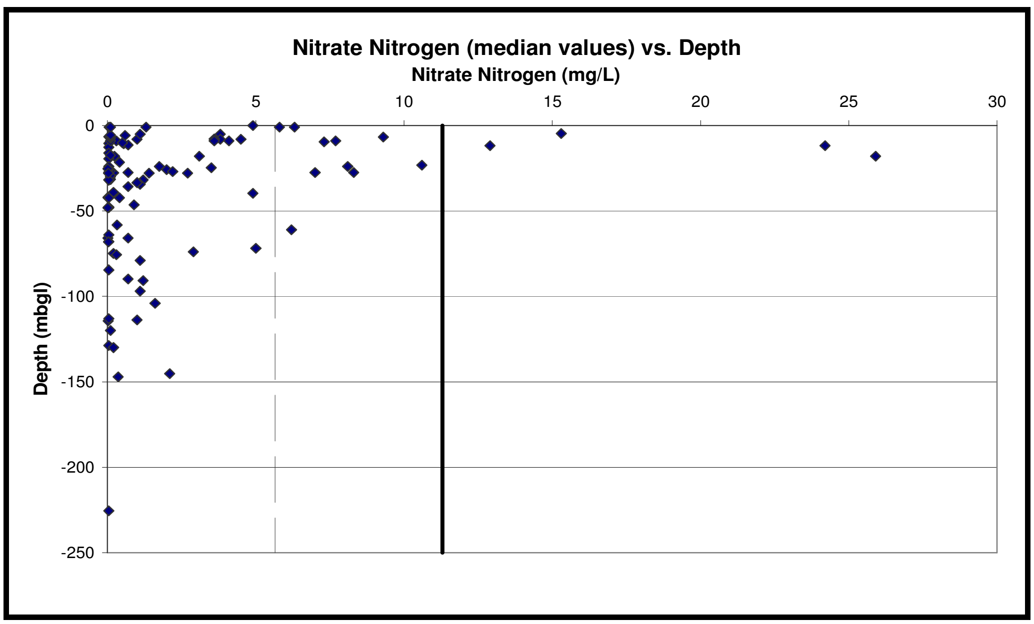

Figure 4.5 Median concentrations of Nitrate Nitrogen plotted against depth. NB solid vertical line indicates MAV DWSNZ (2005) = 11.6 mg/L, dashed vertical line is half the MAV = 5.7 mg/L.

There are four wells with median concentrations exceeding the Arsenic MAV (DWSNZ, 2005). Three occur near Saltwater Creek with the other located just down gradient from the Amberley Swamp. High Arsenic concentrations have been previously recognised in the Saltwater Creek area (PDP, 2001).

4.3.5 Redox states

Table 4.7 shows average concentrations of determinants by class. It should be noted that the values for DO reflect the assumptions of the classification rather than any inherent trends. The difference between groups for Ammonia Nitrate, Arsenic and Sulphate are small and are not significant. Manganese concentrations are not significantly different between classes though the reduced class had a large interquartile range. There was a significant difference between the Oxidised and Reduced classes for Iron and Nitrate Nitrogen.

Table 4.7 Average values for the Redox classified groups. Figures in bold are considered to be significantly different.

No.	Redox state	Depth	NH_4	As	Fe	Mn	NO_3-N	SO_4	DO
		mbgl	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
2	Complex	-62.9	0.058	0.002	0.20	0.210	0.1	4.0	3.17
75	Oxidised	-37.4	0.122	0.001	0.34	0.082	**3.0**	19.3	5.89
49	Reduced	-46.4	0.197	0.003	**1.67**	0.388	0.7	15.7	0.42

4.4 Water chemistry discussion

The water chemistry results indicate that the study area could be divided into four Hydrochemical zones. The different chemical signatures from these zones are thought to be related to the type of sediment that the water interacts with, the composition of the recharging water and to a lesser extend land use practises. The divisions are based on the chemical zonation analysis and HCA. The Hydrochemical zones are referred to as Saltwater Creek, Downlands, South Waipara and North Waipara. These Hydrochemical zones are shown in Figure 4.6.

Groundwater recharge interpretations are presented for each Hydrochemical zone where able.

4.4.1 North Waipara

The North Waipara zone encompasses the Omihi Valley Southward to the Waipara River (Figure 4.6). The chemical zonation analysis showed that this zone has the highest median concentrations of Bicarbonate, Calcium, Sulphate, Bromide, Hardness, TDS and Conductivity (Appendix4c). The HCA showed that generally on the margins sites defined as subgroups 3.2 and 2.1 are found with subgroup 3.3

located centrally. This HCA pattern reflects a decrease in ionic loads towards the centre of the basin.

The Geological map of the area shows that North Waipara Hydrochemical zone is ringed by Tertiary sediments. Bore logs from the area North of the Waipara Township reveal that limestone clasts are recorded in more than half the wells[6] (Total wells in this region with bore logs n=47). Previous workers have suggested that the alluvial fill in this region will contain significant Tertiary clasts, occasional secondary redeposited gypsum and secondary redeposited calcium carbonate (Harris, 1982. Finnemore, 2004). It is proposed that the water chemistry in this zone is dominated by interactions with the alluvial fill.

In the Wanaka and Wakatipu basin Rosen and Jones (1998) found groundwater chemistry was controlled by dissolution of Calcite as when these determinants (in meq/L) were plotted they fell on a 1:1 line. This is because after taking into account the charge difference the dissolution of Calcite in the present of water produced equal proportions of Calcium and Bicarbonate (Rosen, 2001). Figure 4.7 is a scatter plot of Calcium versus Bicarbonate in milliequivalents per litre by Hydrochemical zone. Many of the sites in the North Waipara zone plot near the 1:1 line and in the upper part of the graph however the regression for this zone is not 1:1 (it is $y=0.61x + 1.59$, $r^2=0.75$). Given this and that there is significant limestone clast present in this zone suggests that calcite dissolution is occurring but other water rock reactions are also taking place. From Figure 4.7 we can see most the wells and springs in this zone plot above the 1:1 line indicating a greater proportion of Bicarbonate relative to Calcium.

Figure 4.8 is a plot of Sodium and Chloride by Hydrochemcial zones. The black line in the figure is the saltwater concentration-dilution (SDCL) line taken from Rosen (2001) shown here to represent a seawater ratio. None of the wells or springs in this zone falls on the line. Sites from this zone plot on both sides of the SCDL, over a large area.

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[6] The assumption is that limestone clasts being for the most part quite distinctive would be noted by drillers. The Limestone units are located approximately midway in the sedimentary sequence means that there are likely to be at the very least remnants of the sediments overlying the limestone in the basin fill also.

Figure 4.6 Spatial distribution of the subgroups defined in the HCA. Shown also are the boundaries of the Hydrochemical zones.

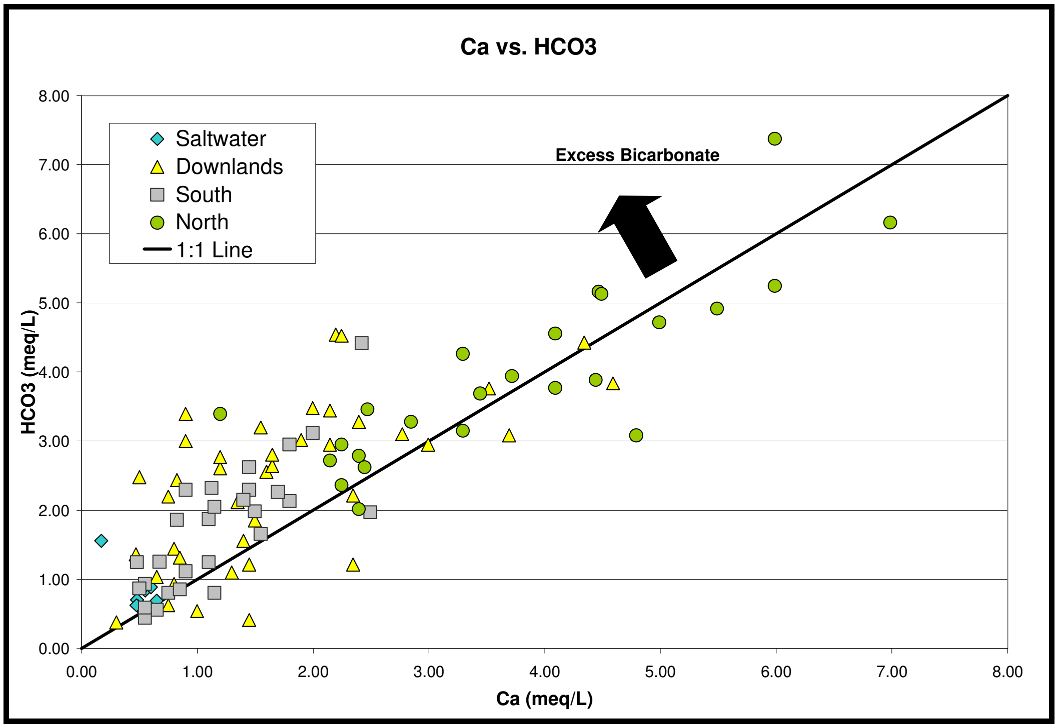

Figure 4.7 Scatter plot of Ca and Bicarbonate (meq/L) by Hydrochemical zone. Median data from springs and wells is used. Black solid line is a 1:1 line plotted for reference.

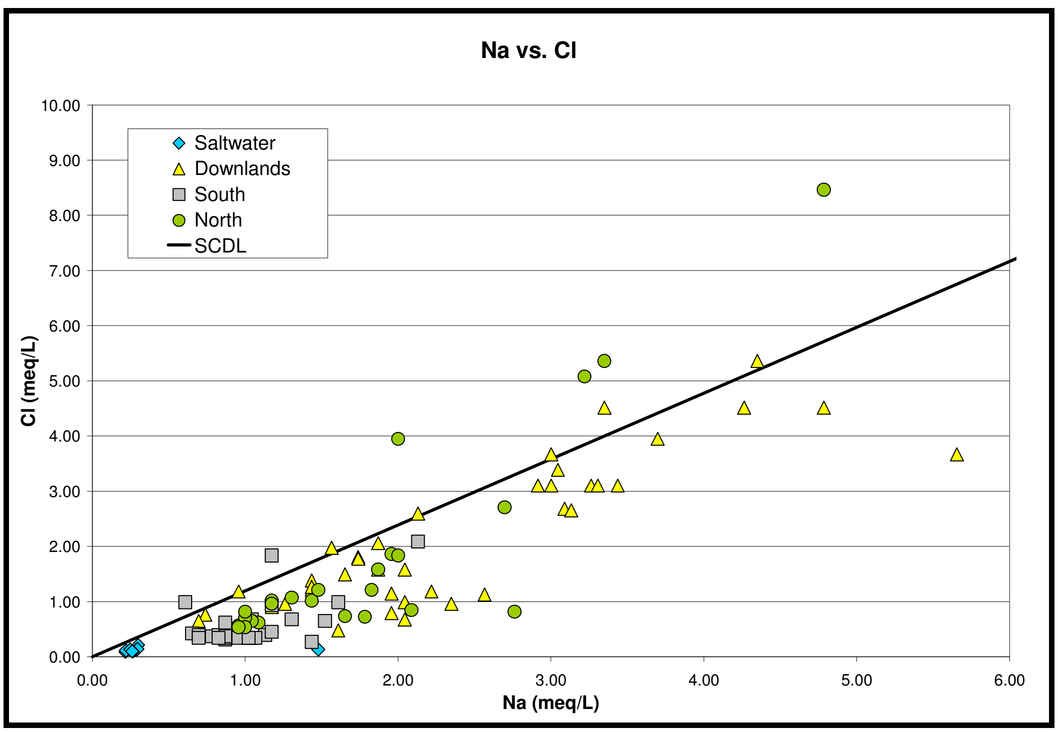

Figure 4.8 Scatter plot of Sodium versus Chloride by Hydrochemical zone. Median data from springs and wells is used to construct the graph. The black line is the saltwater concentration-dilution line (SCDL) from Rosen (2001).

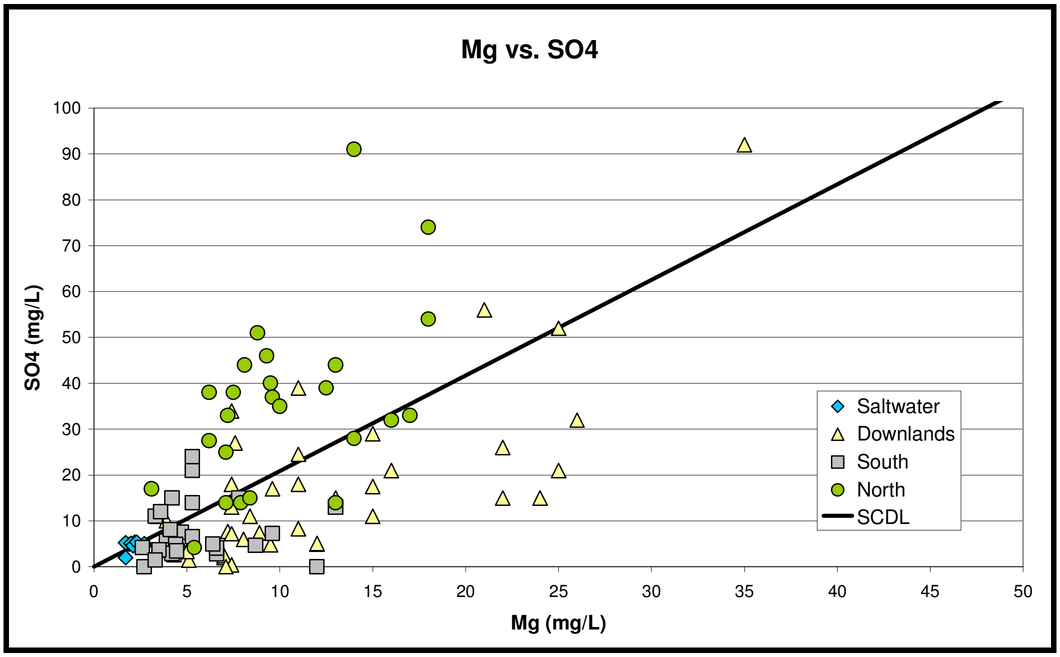

Figure 4.9 Scatter plot of Magnesium versus Sulphate by Hydrochemical zone (in mg/L). Median data from springs and wells is used to construct the graph. The black line is the saltwater concentration-dilution line (SCDL) from Rosen (2001).

Figure 4.9 is a scatter plot of Sulphate and Magnesium by Hydrochemcial zone. The majority of the sites in the North Waipara zone plot above the SCDL indicating the dissolution of Pyrite or Sulphate minerals (gypsum) are the most likely cause of this data distribution. When plotted spatially Sulphate concentrations decrease towards the centre of the basin (also true for most determinants in this zone).

Spring N34/0165 and Omihi Stream (SQ35397, Appendixand Table 4.3) were sampled during the course of this study. Both sites are located in the lower reaches of the stream before the confluence with the Waipara River. N34/0165 is a single vent, part of a spring “cluster” with numerous discharge points (section 3.2.7). Anecdotal evidence suggests that Omihi Stream is typically dry during Summer just upstream from these sites (per com. B Harris, 2008). Visual gauging observations show that the Omihi stream downstream from this cluster of springs was always flowing when visited in 2008. The ion concentrations from these two sites are similar to the median concentrations for the North Waipara zone. This suggests that the source of recharge to these springs is from groundwater flowing Southward from the Omihi valley and Southeast from the Waipara Downs fan system (Figure 4.6). The only other surface water site sampled for major ion chemistry is a spring in Home Creek, N34/0162

(Loris, 2000). Again the ion concentrations from this site are similar to the median concentrations for the North Waipara zone.

Lloyd (2002) demonstrated that Home Creek, Omihi Stream and Weka Creek have significant losses to groundwater. However there is limited major ion chemistry for surface water sites in the Waipara Basin apart from the Waipara River. Chemistry data from shallow wells (depth <26mbgl) that are located within 200m from a stream and with water levels that appear to be similar to that of the nearby stream were looked at to provide an estimate of the chemical composition of the surface water (N34/0058, N34/0097 and N34/0132). Using this very crude method no obvious trends were detected suggesting that major ion chemistry is primarily reflecting water rock interactions and is less useful in determining recharge sources within this zone.

4.4.2 South Waipara

This zone includes the area Southwards of the Waipara River to the Broomfield Fault (Figure 4.6). The median concentrations for most determinants are lower than those for the North Waipara zone (Appendix 4c) and significantly lower in the cases of the determinants listed in Table 4.4. From the HCA subgroups 3.1, 2.2 and with minor 3.3 were found in this zone.

The geological map of the region shows that the flanks of this zone are composed of Kowai Formation which overlay the Tertiary sediments. The user defined function in the Aquidef program[7] (Davey, 2004) was used to find if any bores in this region had limestone listed in the strata descriptions of the bore log. Limestone clasts were listed in the descriptions at of at least one well at the depth of 85mbgl and below. Bore logs from three of the deepest wells in this zone were examined (M34/5540, M34/5608 and M34/5707). The bore logs indicated gravels, sands, silts and muds but there is no obvious reference to Tertiary sediments.

Chloride concentrations in this zone typically range from 10 – 20 mg/L (shown as meq/L in Figure 4.8). Haywood (2002) suggested that wells in the Christchurch – West Melton groundwater allocation zone that were recharged by rainfall typically

[7] Aquidef produces a histogram using data from Environment Canterbury's wells database. The user defined function allows the database to be interrogated and the results presented as a histogram vs. depth plot.

had Chloride concentrations in this range. The sediments in that region like the South Waipara zone are dominantly composed of derivatives of the Torlesse super group. The Torlesse super group are composed of quartzo-feldspathic clasts (Bradshaw, 1989) which are likely to be relatively inert. In support in the North of this zone Subgroup 3.1 sites are common, particularly in shallow wells. This subgroup has a low ionic load but a relatively high Nitrate Nitrogen content (Table 4.5).

Lloyd (2002) suggested this zone was primarily recharged by rainfall on the basis that the Waipara River does not appear to loss water to groundwater along the length between the two gorges. In addition there are only a small number of ephemeral streams and drains on the basin floor within this zone so any input from surface water is likely to be minimal. Losses from the Kowai River (NB) and major tributaries may contribute to the Southwestern margin (section 3.5.1). Using median Summer flows (from three gaugings) 24 l/s was lost to groundwater (section 3.2.4).

Chloride values in this zone increased in wells near the Teviotdale hills. Field observation of springs that appeared to the North and West around this feature following significant winter rainfall suggests that this area is being recharged from rainfall falling on the Teviotdale hills and flowing Westwards down topographic gradient into the basin. The increased Chloride concentrations may reflect the longer groundwater residence times or perhaps interaction of this water with marine sediments of the Kowai Formation. A similar spatial pattern is detected for Sulphate, Sodium and Magnesium which indicates interaction with soluble salts. Results from the HCA analysis support this conclusion.

The spatial pattern revealed from the HCA can be in interpreted in terms of flow patterns in the Southern part of the basin. Figure 4.6 shows along the Southern margin of these zones shallow wells belong to subgroup 3.1 and deeper wells belong to subgroup 2.2. Near the Broomfield Fault all the wells are defined as being part of subgroup 2.2. This is interpreted as upward movement of deeper groundwater (Figure 4.10). This proposition is supported by water level observations (see section 3.5.2). These results, geophysical investigations (2.3.2), surface water observations (section 3.2.4) and water level observations (section 3.5.2) clearly indicate that the Broomfield

Fault is a hydrological boundary. As such it seems to be a logical boundary between the Kowai and Waipara groundwater allocation zones.

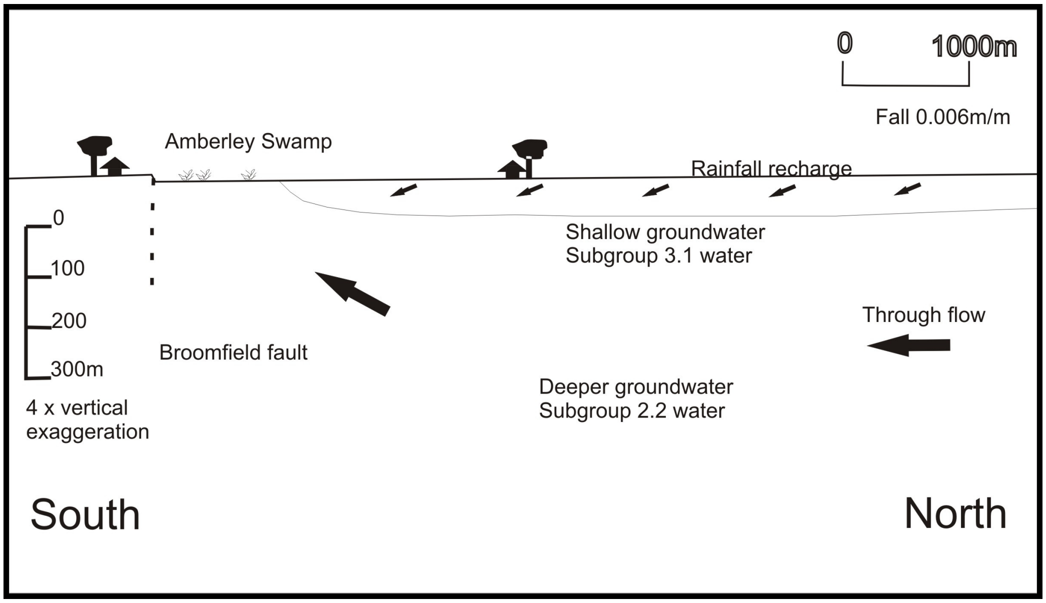

Figure 4.10 Conceptual model for the spatial distribution of the results from HCA for the South Waipara Hydrochemical zone. Note that Broomfield Fault dip is inferred and the light black light dividing subgroup 3.1 from 2.2 is not a lithological contact or a flow line. It is drawn only to depict separation between the two subgroups.

4.4.3 Downlands

The Downlands zone is the area between the Broomfield Fault Southwards to about Sefton (Figure 4.6). This zone is has the highest median concentrations of Chloride, Sodium, Arsenic, Iron, Manganese, Magnesium and Reactive Silica. This zone has relatively high concentrations most of the other determinants except Nitrate Nitrogen in which it has overall lowest median concentration (Appendix 4c and Table 4.4). Almost all HCA subgroups are represented in this zone.

Figure 4.2 and Figure 4.6 show the spatial distribution of TDS and the HCA. Both figures suggest a complex pattern however generally TDS concentration in wells seems to be lower near ephemeral streams and both braches of the Kowai River. Water level data discussed in section 3.5.1 showed that shallow wells are being recharge by proximal ephemeral streams.

Examination of the limited bore logs from wells greater than 100m total depth show a variety of lithologies; gravel, sand, mud, clay, peat and silt. Aquidef when plotting all the wells with bore logs show that the sediments are dominated by claybound gravels. There are no obvious descriptions referring to Tertiary sediments in any of the bore logs examined by the author.

Table 4.8 Average rainfall chemistry from long term (5 – 12 years) sampling from Nichol et al (1997). Kelburn is a coastal site located in Wellington, Lauder is located in central Otago and Puruki is a forested site located near Rotorua.

	Kelburn (M8389)	Kelburn (M9091)	Kelburn (F9192)	Lauder (M8391)	Lauder (F9194)	Puruki (M8791)
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
SO4	1.89	1.41	1.43	0.18	0.12	0.74
Cl	9.00	8.38	7.45	0.62	0.21	1.11
NO3	0.03	0.02	0.04	0.02	0.02	0.04
Na	4.91	4.72	4.24	0.32	0.11	0.63
K	0.19	0.22	0.20	0.09	0.03	0.11
Ca	0.25	0.16	0.92	0.11	0.03	0.13
Mg	0.55	0.49	0.04	0.05	0.01	0.07

The Chloride median concentration for this zone is 63 mg/L, ranging up to 190 mg/L (shown in meq/L in Figure 4.8). Hem (1992) and Hounslow (1995) state that Chloride are typically sourced from seawater, rainwater (Table 4.8), connate seawater, or from soluble salts within porous sediments that have been submerged in seawater. Chloride bearing minerals in igneous rocks are a less common source. Moore (1995) suggested that high concentrations of Chloride detected at Amberley Beach golf course wells (N34/0062, Figure 4.1) was related to sea spray. Figure 4.1 shows that the concentration of the Chloride in the deepest of the wells increased until 2000 after which it has remained at similar concentrations suggesting a change in Chloride input. N34/0062 and nearby wells have been identified as being susceptible to saltwater intrusion due their to vicinity to the coastline (Aitchison-Earl et al 2003). Saltwater intrusion may well be contributing factor to the Chloride levels in wells within a couple of kilometres from the coast, however, wells further inland cannot be affected by this process. This interpretation is supported by the fact that the total depths of many of these wells are less than the depth to mean sea level. High concentrations of Chloride are detected in the Downlands and North Waipara zone but not Saltwater Creek and South Waipara zone. This suggests that sea spray or rainfall is not the dominant source of Chloride to the study area. Furthermore, loess of the Downlands does not have any obvious accumulation of salts in their profiles (per com. P Tonkin, 2009). Connate seawater is discounted as the dominate source of Chloride as flushing of the system should have removed it from the system. Given the arguments above it is suggested that the majority of the Chloride in the study area is from soluble salts contained within the sediments.

The interpretation of the Chloride being sourced from the salts within the sediments is supported by geomorphic and geological observations (section 2.5.1) which suggest that the sea in recent geological history has transgressed into this area.

Figure 4.7 and Figure 4.9 indicate that the Downlands zone typically have excess Bicarbonate when compared to Calcium, and less Sulphate than the North Waipara zone. On both plots this zone has a large scatter which is reflected by the results from the HCA and in the Piper plot.

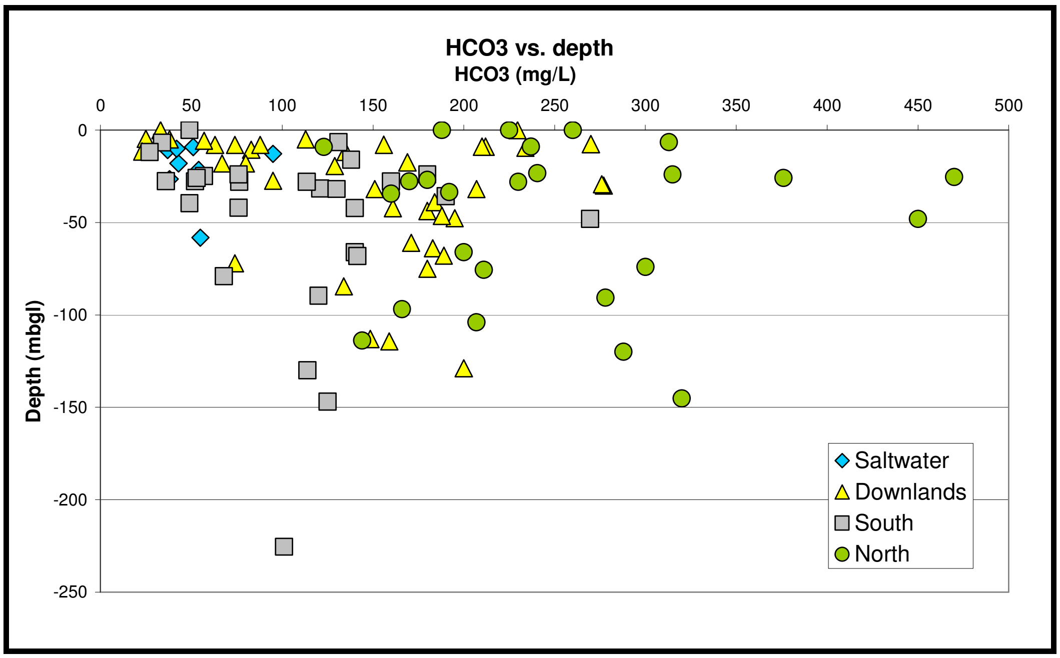

Figure 4.11 Bicarbonate versus depth by Hydrochemical zone

Comparing the results from the HCA to the classification of redox state reveals an interesting pattern in this zone. Group 2 sites are have been typically classified as reduced or complex and group 3 as oxidised. Group 3 sites in this zone are usually shallow (median -9.0 mbgl, n=19, containing four sites >20 mbgl) and Nitrate Nitrogen concentrations >1.0 mg/L. Group 3 are deeper (median -35.5 mbgl, n=20), contain <1.0 mg/L Nitrate Nitrogen. Figure 4.11 and Figure 4.12 show a general increase in bicarbonate with depth and a general decrease in Sulphate concentration with depth. This pattern would be expected for reduced groundwater (Rosen, 2001).

Reduced groundwater is caused by the consumption of available oxygen in a closed system. PDP (2001) suggested that the sporadic occurrences of Arsenic (± Iron and Manganese) in the Saltwater Creek – Waikuku area are a result of groundwater interacting with silts, clays and peat. Similar conclusions were found by Nickson et al. (2000).

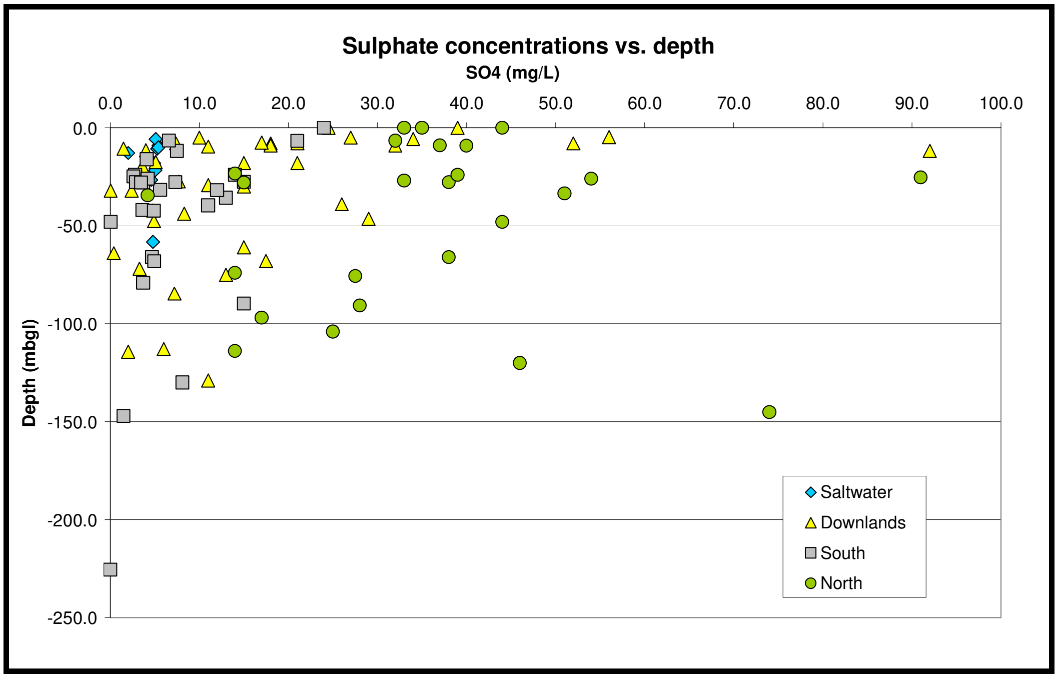

Figure 4.12 Sulphate versus depth by Hydrochemical zone.

4.4.4 Saltwater Creek

The Saltwater Creek zone is bounded to the South by the Ashley River, to the East by the Pacific Ocean and to the Northwest by the loess mantled Downlands. This zone defined on the geomorphic map as surfaces formed <4 ka. In section 2.2.2 the sediments beneath the surface where described as generally alternating sequences of gravel and fine grained material interpreted as the Northern extension of the Christchurch – Kaiapoi artesian system. From the HCA Ashley River water and wells to the South of Saltwater Creek were assigned to group 1. The chemistry of the groundwater in this zone is very different from the other Hydrochemical zone (Table 4.4 and Appendix 4c). The concentration of most ions in this zone are significantly lower that the other zones.

Wells in the South of this zone typically have TDS values less than <100 mg/L and Chloride values less than 10 mg/L. The Ashley River and tributaries have been sampled at ten sites with average value of TDS of 72 mg/L and Chloride of 7 mg/L. Surface water gauging shows that downstream of the confluence of the Okuku and Ashley Rivers to at least State Highway One significant water is lost to groundwater (see section 3.2.5). The results from the HCA and Piper plots show similar trends and clearly indicate that this zone receives significant recharge from the Ashley River; probably moving through predominately Torlesse super group derived sediments. Haywood (2002) identified river recharge from Waimakariri River by Chloride concentrations ≤10 mg/L.

Near the mouth of Saltwater Creek and along the Southern margin of this zone the chemistry of the water is different in that the concentrations of ions are slightly higher. The spatial pattern suggests mixing of Ashley River derived recharge and water exiting from the Downlands zone. A sample taken from the Saltwater Creek at McGifferts Road near its spring fed source show a slightly elevated concentration of TDS, Chloride, Sodium, Ammonia Nitrate and Sulphate. Samples from Boyne Creek at Broad Road are similar to the sample taken from McGifferts Road. Visual gauging and spring mapping indicate that Boyne Creek is at least partially spring fed upstream from this sampling site. Boyne Creek and Saltwater Creek are tidal several kilometres inland but not as far inland as McGifferts Road.

4.4.5 Mixing between zones

Loris (2000) suggested that decreasing hardness and TDS Southwards in the Waipara Basin reflected mixing of waters. To test this proposal a series of plots were constructed (Figure 4.13 and Figure 4.14).

Figure 4.13 shows the sum of Sodium and Chloride versus Calcium and Bicarbonate, which is meant to show the influence of salt and calcite groundwater. There appears to be a continuum between the two zones. Figure 4.14 is the sum of Bicarbonate and Sulphate and Calcium and Magnesium taken to represent the influence of calcite and gypsum on the groundwater. There is a good fit for all the data shown ($R^2 = 0.89$) and a continuum between North and South Waipara zones. This suggests that groundwater is flowing and becoming more dilute Southwards. It also suggests that Calcite and Gypsum control the composition of the groundwater in the Waipara Basin.

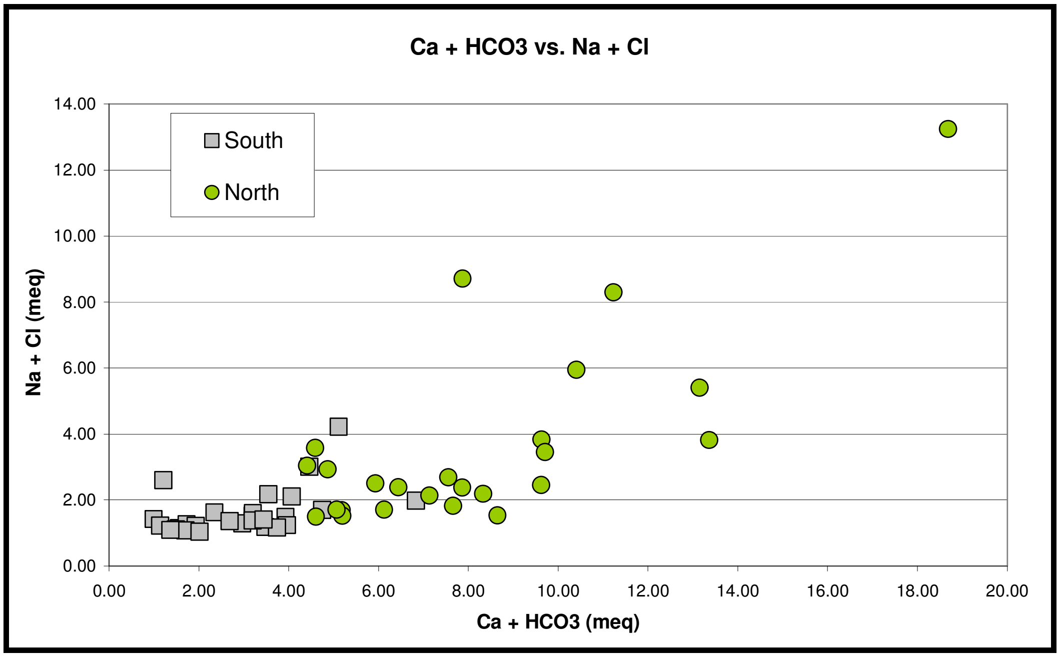

Figure 4.13 Scatter plot using median data from the North and South Waipara Hydrochemical zones.

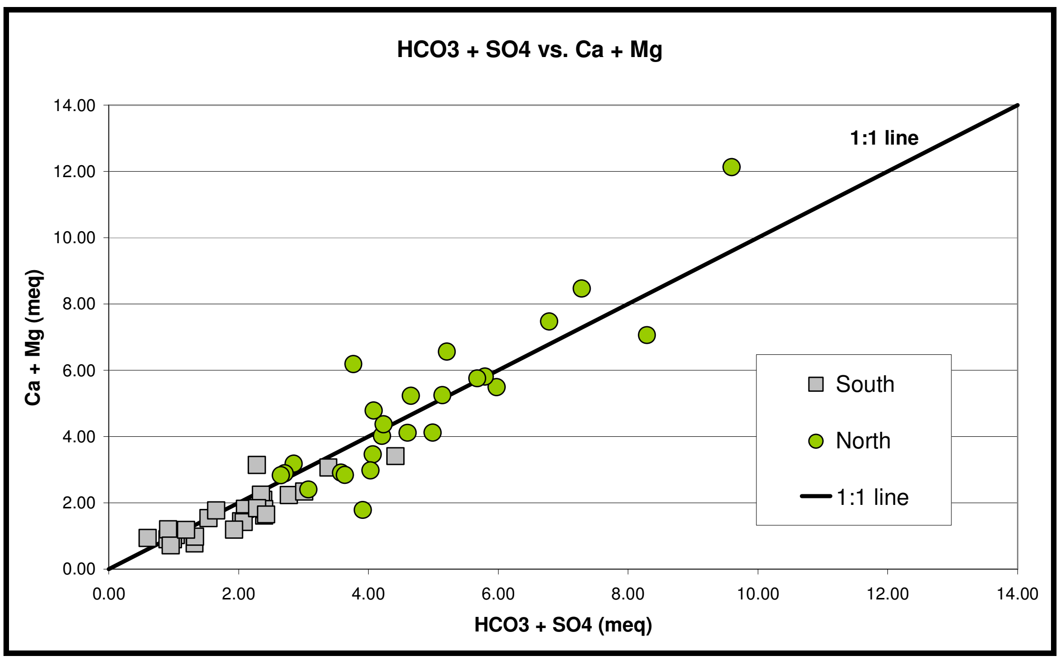

Figure 4.14 Scatter plot using median data from the North and South Waipara Hydrochemical zones. The black solid line is a 1:1 line plotted for reference.

Mixing of Downlands and Saltwater Creek zone waters were discussed in section 4.4.4. There is not enough chemical information to determine mixing between the South Waipara and Downlands zone near Amberley though it is inferred from other methods (section 3.5.1).

4.5 Summary

A large amount of water chemistry data is available for sites within the study area and an attempt has been made to use this data (Appendix 4b – 4e).

The data once compiled into medians and viewed spatially showed that four zones could be defined; Saltwater Creek, Downlands, South Waipara and North Waipara zones. Box & whiskers plots were constructed to test the differences between the zones (Table 4.4). HCA was conducted as an objective test of the data.

The results of the HCA and chemical zonation analysis were used to define four Hydrochemical zones being: Saltwater Creek, Downlands, South Waipara and North Waipara zones.

Saltwater Creek zone is recharged primarily by the Ashley River but also with contributions from the loess Downlands. The Downlands zone is quite complex. Recharge occurs from ephemeral streams, losses from Kowai River (both branches) and rainfall. The high concentration of chloride in this zone is interpreted to be sourced predominantly from soluble salts within the marine material intercalated with the fluvial deposits. Wells near the coast are susceptible to saltwater intrusion and this may also contribute to chloride levels.

The South Waipara zone is primarily recharged by rainfall which is reflected in the chemistry of the water. It is interpreted that this zone also receives recharge from the Teviotdale hills. The North Waipara zone water chemistry reflects interaction with the clasts of Tertiary sediments that occur within the alluvial fill. Dissolution of Calcite and Gypsum is interpreted as controlling the composition of the groundwater. Generally the chemistry of the waters in the North and South Waipara zones appear to decrease in ionic loads Southwards and towards the centre of the basin due to mixing of waters of different origins.

The Broomfield Fault is interpreted to be a hydrological boundary. As such it is a logical boundary between the Kowai and Waipara groundwater allocation zones.

5 Chapter five: Stable isotopes and groundwater dating

5.1 Introduction

Oxygen and Hydrogen stable isotopes have been used extensively as tracers for groundwater studies (Taylor et al, 1989, Stewart et al 2002). The stable isotopes of meteoric water vary as a consequence of altitude, latitude, temperature and rainout effects (Gat, 1996). As such, water entering the groundwater system is assumed to carry that isotropic signature which can be used to differentiate recharge sources as long as there is significant contrast between them. For the purpose of this chapter the stable isotopes of water are used to identify recharge and where possible estimates of proportions of recharge from two sources.

^{14}C Groundwater dating has been conducted on six relatively wells deep wells (>60 mbgl) in the study area. A single spring has been dated using SF_6 , CFC's and tritium. Groundwater dating here has been conducted to get a better understanding of recharge rates but has also been used to infer information about the geometry of the basin. Using data CFC's and tritium data from Loris (2000) recharge rates have been estimated using the methodology of Delin et al. (2006).

5.2 Stable isotope methods and theory

Oxygen and Hydrogen stable isotopes were analysed at University of Canterbury's (UC) Stable Isotope laboratory using a high temperature conversion elemental analyser (TC/EA) with analytical errors (±one standard deviation) of Oxygen ±0.1‰ and Hydrogen ±1.0‰.

Isotopic compositions were normalized to the Vienna standard mean ocean water (VSMOW) scale which was defined by the International Atomic Energy Agency (IAEA) in 1968. This normalisation was based on replicate analyses of certified reference materials including Greenland Ice Sheet Project (GISP), Standard Light Antarctic Precipitation (SLAP), and SMOW2. The VSMOW defines modern ocean water as $\delta^{18}O = 0 \pm 0.1$‰ (Clark and Fritz, 1997). The ocean is the largest source of water in the hydrologic cycle and has a relatively uniform oxygen and hydrogen stable isotopic composition. This water body undergoes evaporation which produces water vapour which rises into the atmosphere and eventually returns as precipitation (i.e. the hydrological cycle). During the evaporation of the ocean Oxygen and Hydrogen stable isotope undergo fractionation where the more abundant lighter isotopes (^{16}O and ^{1}H) are preferentially evaporated due to kinetic effects associated with the liquid-vapour phase transition (Clark and Fritz, 1997). Due to the vast volume of water in the ocean, its isotopic composition does not change in the short term (<hundreds of years) but the evaporated δ-value of water vapour and subsequent δ-value of resultant precipitation become negative relative to sea water (reference delta notation, Figure 5.1).

Delta Notation

$$\delta = \{[(R_{samp.})/(R_{std.})]-1\} * 1000$$

$$\delta^{18}O = \{[(^{18}O/^{16}O)_{samp})/(^{18}O/^{16}O_{std})]-1\}\times 1000$$

$$\delta D = \{[(^{2}H/^{1}H)_{samp})/(^{2}H/^{1}H_{std})]-1\}\times 1000$$

Element	Isotope	Abundance (%)
Hydrogen	1 H	99.985
	2 H	0.015
Carbon	12 C	98.89
	13 C	1.11
Oxygen	16 O	99.759
	17 O	0.037
	18 O	0.204

Figure 5.1 Top Delta notation used to calculate stable isotope ratios. Bottom the abundance of stable isotopes for the elements Hydrogen, Carbon and Oxygen. Source T Horton.

Two fractionation processes affect the stable isotopes of water: Kinetic fractionation which occurs during evaporation of ocean water (sensitive to boundary layer relative humidity) and Rayleigh fractionation of water vapour in an air mass. The isotopic composition of water vapour in the atmosphere is essentially controlled by changes in temperature (Gat, 1996). Water vapour masses rainout as they move toward areas of lower temperatures .i.e. higher altitudes and lower latitudes (IAEA, 2009). Under these circumstances water vapour becomes progressively depleted in rarer heavier isotopes relative to common lighter isotope resulting in progressively more negative δ values.

Craig (1961) found that hydrogen and oxygen stable isotopes derived from an oceanic source have a linear trend, expressed as $\delta D = 8 \times \delta^{18}O + 10$ at the global scale. This equation represents a global average obtained from surface water sites though it has been subsequently found that localised variations (e.g. climate) will change the form of the equation thus producing local meteoric water lines that can vary in slope and deuterium excess by as much as X units and Y‰, respectively.

5.3 Sampling programme

To help define inputs and outputs from the Groundwater System four rivers/ stream, two springs and two rainfall sites were sampled. A flowing artesian well (M34/0192, -18 deep) near Saltwater Creek was also sampled to gauge the temporal changes in stable isotope composition in groundwater (Figure 5.2). The well/springs/rivers are collectively referred to as baseline sites. Sampling of baseline sites was conducted weekly or fortnightly from 18/1/08 (except Omihi Stream, which commenced on the 31/1/08) until the 10/12/08. Rainfall was sampled whenever sufficient rainfall had fallen, sampled mostly at a minimum of weekly intervals.

Sampling procedures for purging wells are the same as described in section 4.2.2. Surface water sites were sampled in the part of the channel where there was a constant flow and springs were sampled as close as possible to the discharge point. Field measurements of DO (mg/L and %), pH, conductivity and water temperature were recorded. Rainfall was collected in rain gauges sited >1m above ground level to avoid rain splash and where possible away from obstructions such as shelter belts. The Duff Road site had obstructions to the South and North that may have affected the amount of rain collected. 3 – 4 mm of Castrol HS32 oil was added to the gauge to minimise evaporation. Cumulative weekly rainfall totals were recorded at each site per visit. All samples were collected in 500 ml plastic bottles with screw on lids. The samples were taken so to minimise the amount of air space in the bottle i.e. at surface water sites the bottles were filled and the lid fitted underwater.

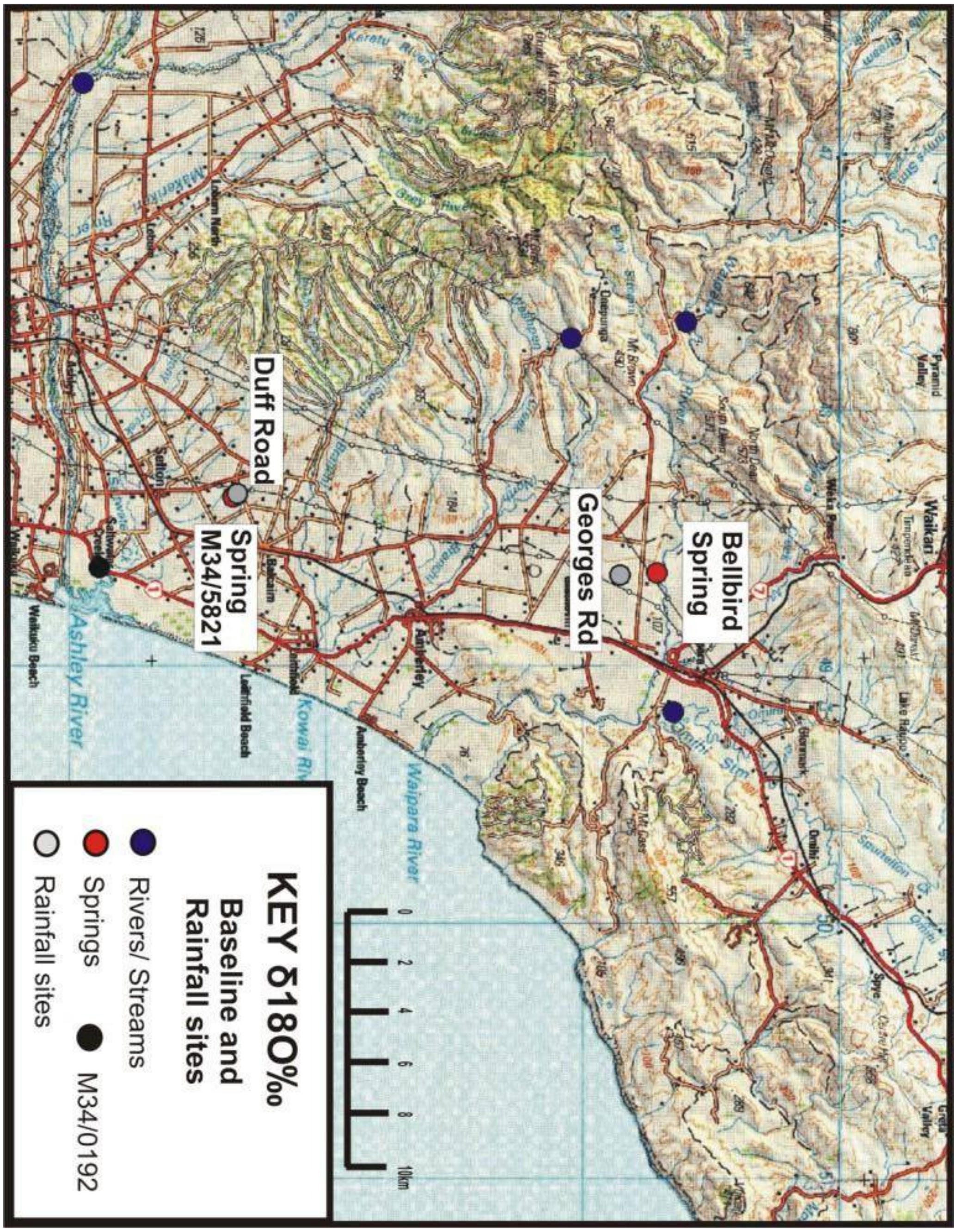

Figure 5.2 Map showing the locations of baseline and rainfall sites sampling over the course of this study.

In April and May 2008, an additional 96 wells, an excavation pit, a spring and 10 surface water sites were sampled. In September and October 2008, 48 wells were revisited and sampled. In September, 11 wells were sampled by Environment Canterbury for their annual groundwater quality sampling programme which were sampled for stable isotopes. During the same period 16 surface water sites were sampled, nine of which were also sampled in April. In September 2008 following the first significant Winter rainfall event the Amberley Swamp discharge and sites upstream and downstream from that point were sampled. Two of these sites were sampled at total of three times of the course of the study. These are collectively referred to as comparative sites.

5.4 Data quality assurance and results

The results of the sampling are shown in Appendix 5a, 5b and 5c.

In a number of the rainfall samples the HS32 oil used to minimise evaporation appeared to become mixed with the rainwater[8]. Potentially this could result in oil oxygen and hydrogen being added to the samples during analysis (per com. T Horton, 2008). The measured $\delta^{18}O$ and δD values at both rainfall sites were predominantly more positive than anticipated (Stewart and Morgenstern, 2001). There were also a small number of samples with delta values that were more negative than expected (Figure 5.3).

To assess the rainfall data at both sites, $\delta^{18}O$ values were plotted against the average cumulative weekly rainfall (Figure 5.3). The most positive $\delta^{18}O$ occurred at the same time of the year. Field notes indicate that this rainfall event was the tail end of a tropical cyclone that passed through the area in mid January. The rainfall $\delta^{18}O$ data in Figure 5.3 shows a clear seasonal trend with more positive values in Summer/Spring and more negative Autumn/Winter. This result is expected given seasonal shifts in zonal circulation patterns across New Zealand. Both rainfall sites have a similar overall pattern however $\delta^{18}O$ and δD average from Georges Road are more negative that the Duff Road. The last Georges Road sample (10/12/08) is an analytical error and has been excluded from any further analysis.

[8] Composed of synthetic hydrocarbons. The technical data sheet for this oil states it is insoluble in cold water.

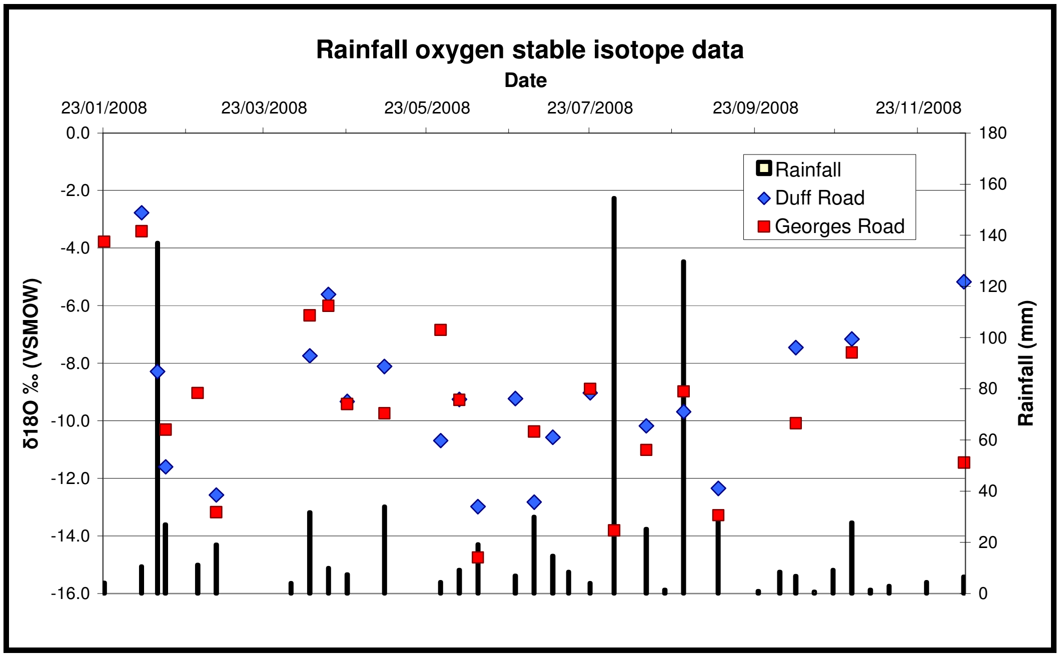

Figure 5.3 $\delta^{18}O$ values from the two rainfall sites located within the study area. Plotted also is the average cumulative weekly rainfall from those sites.

Table 5.1Linear regression equations and coefficient of determination for the weekly sampled stable isotope sites.

Site ID	Linear regression	R^2
Well M34/0192	y = 1.99x - 41.6	0.33
Omihi stream SQ35397	y = 3.66x - 26.1	0.60
Waipara River SQ33962	y = 3.03x - 35.6	0.77
Kowai River (North Branch) SQ35352	y = 4.03x - 21.1	0.79
Ashley River SQ30182	y = 4.61x - 16.6	0.63
Spring M34/5521 (Bellbird Spring) SQ35353	y = 3.51x - 26.3	0.63
Spring M34/5821 SQ35354	y = 5.07x - 10.4	0.87
Rainfall site (Georges Road) SQ35356	y = 6.70x + 3.6	0.89
Rainfall site (Duff Road) SQ35355	y = 7.48x + 10.3	0.91

To further test the rainfall data it was plotted against a local meteoric water line (LMWL), where the LMWL for Canterbury has been calculated as $\delta D = 8 \times \delta^{18}O + 10$ (Stewart et al, 1983 as cited in Stewart and Morgenstern, 2001). The LMWL was determined from average annual δD rainfall data. Table 5.1 shows that Duff Road has a linear regression equation close to the LMWL while Georges Road has a lower intercept and a shallower slope. Given this and the similarities of the overall patterns shown in Figure 5.3 it seems that the interaction with the oil has had a minimal effect.

Sampling of the baseline sites commenced in mid January with the expectation that the new stable isotope laboratory at the UC would be operational by April. However, delays in construction and teething problems with the equipment meant that the first samples were run in mid December 2008 after all the sampling had been completed. The analysis was completed by the end of December 2008. A potential problem is that after relatively long periods of time the samples may interact with the atmosphere altering the isotopic composition.

To test if this had an impact on the results a series of tests were conducted on the data. Initially to evaluate the baseline sites they were compared to the LMWL (Figure 5.4, Table 5.1 and Appendix 5a) From Table 5.1 we see that M34/0192 has low coefficient of determination which reflects the fact the data plots as a relatively tight group. The other baseline sites have more linear spread to the data which equates to a higher R^2 value. Visually inspecting the scatter plots (Figure 5.4 and Appendix 5a) shows that most of the baseline data plots close to but above the LMWL. Surface water baseline sites responded isotopically in a similar manner to climatic events (Appendix 5b). Given this and bearing in mind the climatic extremes that occurred over the course of the sampling period (refer to section 3.2.1) these results seems reasonable. However the averages from these data are likely to be higher than long term averages.

The first test of the comparative sites was to compare $\delta^{18}O$ values from the same site obtained from this study to data held by Environment Canterbury analysed at IGNS. The average difference for the entire data set (n=29) is -0.33‰ (UC $\delta^{18}O$ minus IGNS $\delta^{18}O$), with minimum and maximum differences of 0.56 to -1.19. Environment Canterbury as a part of the 2008 Groundwater quality annual survey collected $\delta^{18}O$ samples. For wells located in the study area an additional stable isotope sample was collected and analysed at UC. This means samples collected on the same day, using the same sampling procedures were analysed at two separate stable isotope laboratories (n=8). The average difference between the two laboratories using only these 8 samples was -0.49‰. Minimum and maximum differences are -0.16 to -0.90‰.

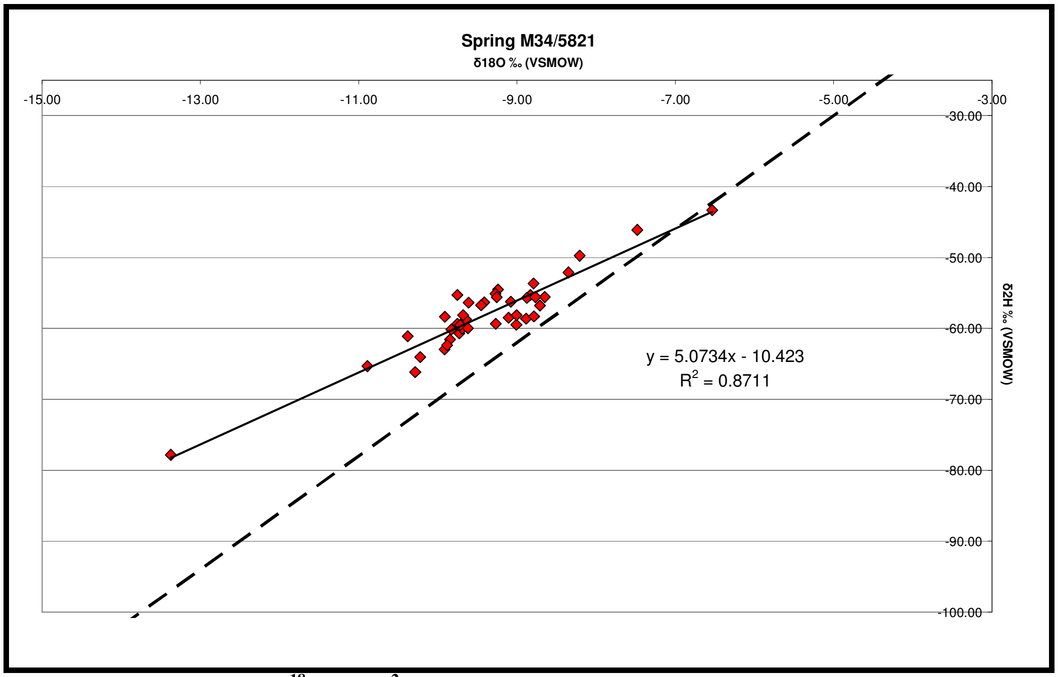

Figure 5.4 Scatter plot of $\delta^{18}O$ and $\delta^{2}H$ for the Spring M34/5521 (Bellbird Spring, SQ35353) baseline site. Dashed black line is the LMWL shown for reference. Solid black line is a linear trend line.

The second test of the comparative data was to compare the δ values obtained from the April – May sampling to those obtained from the October sampling. For $\delta^{18}O$ (n=41) the average difference was 0.02‰, with differences varying from -1.76 to 2.54 (δ Apr minus δ Oct). For δD (n=43) the average difference was -2.29‰, with minimum and maximum differences of 4.27 to -15.78‰.

The comparative sites δ data is shown in Figure 5.5. As sites in this dataset have a maximum of two or three points calculating line slopes for these data would be problematical. Therefore the closeness of the sample plotted relative to the LMWL was used to assess the data (using arbitrarily defined thresholds). The majority of the samples plot on or near the LMWL. However there are a small number of sites that plot well below the LMWL and a larger number of points plotting well above the line.

Using these three methods the stable isotope data from the comparative sites shown in Figure 5.4 were ranked (1, 3, and 5) with the lowest number being reserved for samples that the author had the most confidence in. Those ranked 5 have been excluded from any further analysis (i.e. data circled in Figure 5.5). 68.1% of the data was ranked 1, 30.5% as 3 and only 1.4% ranked as 5 (Appendix 5c).

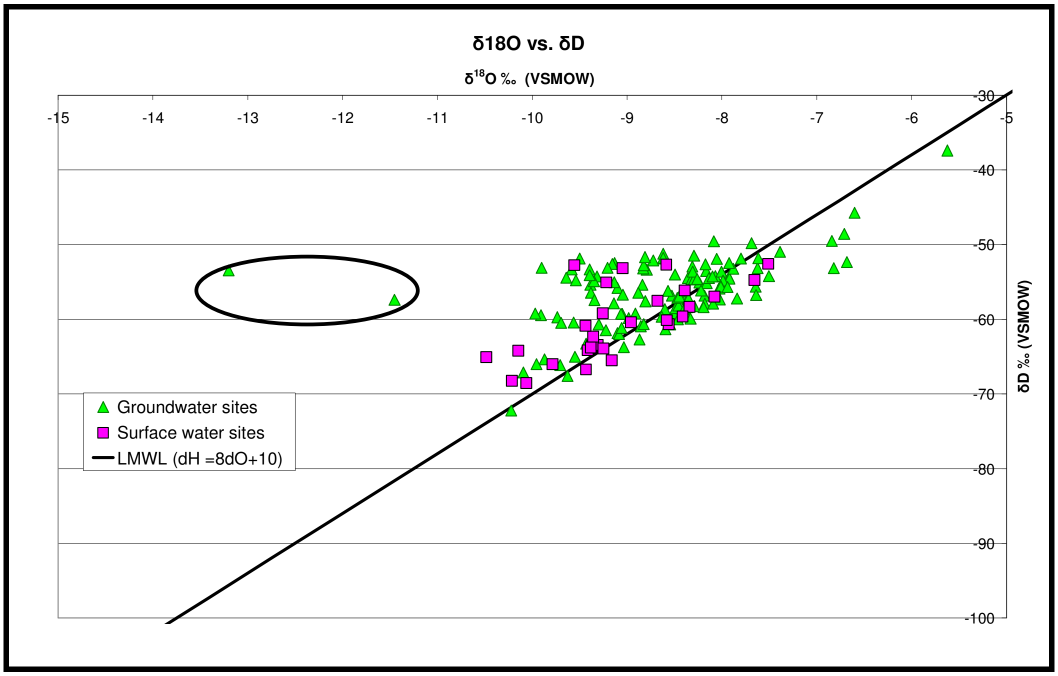

Figure 5.5 Scatter plot of $\delta^{18}O$ versus δD for wells, springs and streams sampled in April - May and September - October. Black solid line is the LMWL shown for reference. The circle encompassed results from two samples that are considered to be erroronous.

5.5 Stable isotope interpretations

5.5.1 Altitudinal changes in $\delta^{18}O$ composition

Stewart and Morgenstern (2001) suggest that for the Canterbury and Otago there is a poor relationship between altitude and δD, whereas Poage and Chamberlain (2001) using published data collected from most of the mountain belts on the planet found good correlations between changes in $\delta^{18}O$ and changes in altitude. The spatial distribution of this study's data and data obtained from rainfall sites on the plains suggest a relationship with altitude (Table 5.2 and Figure 5.6).

Rainfall on the Canterbury Plains has been measured at four locations monthly for just over 5 years producing an overall average $\delta^{18}O$ of -7.81‰. These data fits a $\Delta\delta^{18}O$ of -0.43 per 100m change in altitude (Table 5.2). This relationship has been used to produce an estimate of $\delta^{18}O$ values at different altitudes.

Station	Sampled period	Rainfall	
		Rainfall Amount	$\delta^{18}O$
(est. alt. masl)	Years	mm	‰
Airport (35)	2000 - 2004	536.1	-7.56
Lincoln (15)	2000 - 2004	583.7	-7.38
Winchmore (160)	2000 - 2004	717.6	-8.13
Hororata (203)	2000 - 2004	692.4	-8.17

Station	Δ Est. Alt. (masl)	Δ $\delta^{18}O$ average Rainfall	Δ $\delta^{18}O$ Prediction
Hororata vs. Lincoln	188	-0.80	-0.81
Hororata vs. Airport	168	-0.62	-0.72
Winchmore vs. Airport	145	-0.75	-0.62
Hororata vs. Winchmore	125	-0.57	-0.54
Winchmore vs. Lincoln	43	-0.05	-0.18
Airport vs. Lincoln	20	-0.18	-0.09

Alt. (m)	$\delta^{18}O$ Prediction
0	-7.31
100	-7.74
200	-8.17
300	-8.60
400	-9.03
500	-9.46
600	-9.89
700	-10.32
800	-10.75
900	-11.18
1000	-11.61

Table 5.2
TOP Weighted averages for the period 2000 – 2004 for $\delta^{18}O$ from rainfall sites located on the Canterbury Plains. Source M Stewart, 2009.
MIDDLE Difference in altitude and $\delta^{18}O$ between the rainfall sites. Shown for comparison is the $\delta^{18}O$ Prediction value which is calculated by multiplying $\delta^{18}O$ -0.43‰ by the change in altitude.
BOTTOM Estimates of the $\delta^{18}O$ by altitude using the relationship $\Delta\delta^{18}O$ -0.43‰ per 100m change in altitude.

Poage and Chamberlain (2001) preferred to use data collected in transects over mountain ranges. They avoided using samples from the IAEA isotope precipitation network as these sites would reflect different latitude effects, continental effects and complex localised precipitation patterns. Continental effects are unlikely in New Zealand and the sites are located at similar latitudes. Sturman (1986) found that precipitation patterns over Mid–North Canterbury are similar. It is accepted that the altitudinal spread of these sampling sites is limited (<200m) however Poage and Chamberlain (2001) found that at altitudes <5000m and between the 70º latitudes there was a strong linear relationship between $\Delta\delta^{18}O$ and Δ altitude. Furthermore East coast $\delta^{18}O$ data presented in Chamberlain et al (1999) compared favourable to the altitudinal estimates in Table 5.2. Though the lapse rate calculated for the Southern Alps by Chamberlin & Poage (2000) is much lower being; $\delta^{18}O$ -0.19‰/100m.

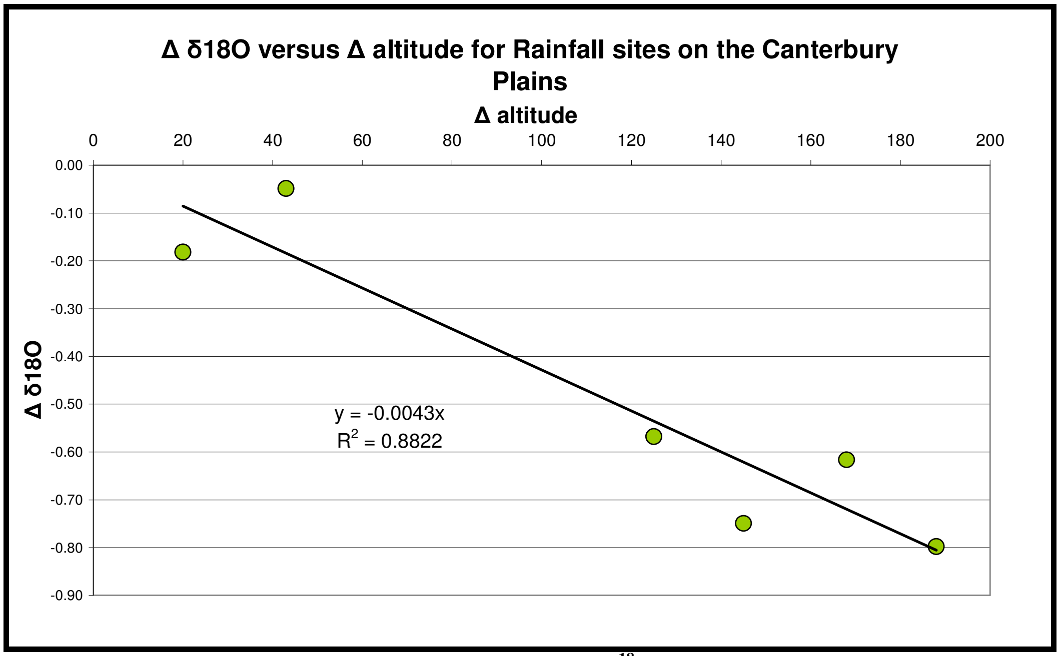

Figure 5.6 Change in altitude plotted against changes in $\delta^{18}O$ for rainfall sites located on the Canterbury Plains. Data used is 5 year weighted means from M Stewart (2009).

5.5.2 Baseline sites

To define the inputs and outputs from the Groundwater system long term average values are preferred. The reason being that short term averages may not take into account the inherent variability of the system considered. As an example the rainfall $\delta^{18}O$ & δD obtained in this study are higher than the average determined for the Canterbury Plains (Table 5.2) and different from $\delta^{18}O$ & δD values obtained during this study for from shallow wells. Furthermore average annual rainfall $\delta^{18}O$ values for the sites shown in Table 5.2 ranged from -6.59‰ to -9.07‰. An attempt was made to find and use pre-existing data sets to give greater confidence to the input averages (Table 5.3). It is assumed that analytical differences are insignificant.

The Ashley River has almost four years worth of $\delta^{18}O$ collected at weekly – fortnightly intervals (Taylor et al, 1989). The sampling locations for the data collected for Taylor et al (1989) and this study are roughly similar, being located downstream from the Okuku confluence (per com. M Stewart, 2008). The average isotopic composition for this site is shown in (Table 5.3).

Table 5.3 Average isotopic composition derived from the baseline sites and average isotopic composition of those sites including all other available data. NB Values in bold are used in mass balance calculations. @ analysed only for $\delta^{18}O$. * denotes the average is based on the entire data set. # δD value has been calculated from the LMWL.

Site ID	Sampling period	Sample count	$\delta^{18}O$ ‰	δD ‰	Source
Well M34/0192	2008	43	**-9.73**	**-61.0**	
Omihi Stream SQ35397	2008	39	**-8.34**	**-56.6**	
Waipara River SQ33962	2008 2000	38 2@	-9.32 **-9.26***	-63.9 **-64.1#**	 Loris (2000)
Kowai River (North Branch) SQ35352	2008	38	**-9.36**	**-58.9**	
Ashley River SQ30182	2008 1979 - 1981	41 120@	-10.26 **-9.34***	-63.9 **-64.7#**	 Taylor et al (1987) & written comms M Stewart, 2009
Spring M34/5521 (Bellbird Spring) SQ35353	2008	43	**-8.97**	**-57.8**	
Spring M34/5821 SQ35354	2008	41	**-9.38**	**-58.0**	
Rainfall site (Georges Road) SQ35356	2008	21	-9.41	-58.0	
Rainfall site (Duff Road) SQ35355	2008	21	-9.17	-58.3	
Plains Rainfall	2000 – 2004	?@	**-7.81**	**-52.5#**	Written comms M Stewart, 2009

The Ashley Rivers 2008 data (Appendix 5a) becomes progressively more negative from April to November. In response to significant Winter rainfall the isotopic composition of the river became more negative. The first four data points shown in Appendix 5a show a slight evaporation trend. During this period the Ashley River went dry at Rangiora ~9 km downstream of the sampling point. The headwaters of the Ashley River are at an elevation of 1500 masl. Using the relationship derived in section 5.4.1 the $\delta^{18}O$ signature for this elevation would be -13.76‰, significantly higher that the average in Table 5.2. This reflects the fact that the Ashley River receives inputs from a number of rivers along its length (Chater, 2004), that the major inputs to the system are sourced at a lower altitude and this river likely received spill over rainfall from Northwesterlies.

M34/0192 has just under a year's worth of isotopic data (Table 5.3). The standard deviation for the isotopic data is the lowest of the baseline sites suggesting a constant recharge source. The water chemistry clearly indicates that this well is predominantly recharged from the Ashley River. M34/0192 isotopic record is similar to the Ashley River except it does not respond directly to rainfall (Appendix 5a). It is interpreted that this well responded 9 – 10 weeks after the large flows recorded in the Ashley as a result of the July/August rainfall events. Using a mass balance approach (Stewart, 2006) an average of 93% of the water in this well came from the Ashley River (using a median, the estimate would change to 100%).

It is proposed that Spring M34/5821 receives recharge from nearby surface water site, Fox's Creek. Aerial photographs show that this spring is located in a relic channel, presumable a former channel of Fox's Creek. Limited isotopic sampling of Fox's Creek shows a similar composition, though so do all the other streams flowing from Ashley forest which were sampled during this study. In Appendix 5a the first four samples (January – early February) show that this spring was undergoing evaporation. A drain has been cut leading from this spring but partially dammed at the outflow. The interpretation is that the spring was no longer being recharged and the standing water was evaporating leaving an increasingly positive residual (greater proportion of ^{18}O relative to ^{16}O). No flow data for Fox's Creek for this period is available to support this interpretation. M34/5821 responded immediately to July rainfall event, but not to the August rainfall event. The sampling run on the 30 July was conducted during the closing stages of the July rainfall event and therefore this sample may represent late stage rainfall.

The Kowai River (NB) site is located ~300m downstream from a spring emerging from a upper limestone unit in the Mount Brown Formation (refer to section 3.2.7). Upstream from this point during Summer it is often dry. The source of recharge to the spring is interpreted to be rainfall falling on the slope to the North. From the start of the sampling programme to June the isotopic composition was similar (standard deviation for $\delta^{18}O$ over this period 0.21). During Winter the isotopic signature became more negative, particular during and after rainfall. The $\delta^{18}O$ average for the January – June period is -8.78‰ suggesting recharge occurring from less than 400m which is the altitude of the inferred recharge zone to the spring. An interpretation for this pattern is that during Summer only the spring was flowing and in Winter the river began to flow along its entire length which is fed from higher altitudes. No flow data from the river upstream is available.

The isotopic composition of the Waipara River appears to shows a strong response to large rainfall events, flow in the river and season (Appendix 5a). During high flows and during Winter $\delta^{18}O$ are more negative. As a result the Waipara River isotopic data has the largest standard deviations which are depicted in this sites $\delta^{18}O$ & δD plot (Appendix 5a). The headwater of the Waipara River is at altitudes greater than >1000m. The average $\delta^{18}O$ value obtained for this river is lower than the predicted value for this altitude (Table 5.2). This reflects inputs from lower altitudes into the system and inputs from Northwest rainfall.

The 2008 isotopic composition of Bellbird Spring (M34/5521) is shown in Appendix 5a. The $\delta^{18}O$ & δD plot shows a relatively tight cluster of points proven by a low standard deviation. From the $\delta^{18}O$ values against time plot shows a slight seasonal trend and responds to rainfall. It being located near the base of the terrace riser above the Waipara River and the chemistry of the water suggest rainfall recharge. The average isotopic composition suggests a minimum recharge altitude of 400m. It is interpreted then that this spring represents groundwater flow to the North from the Glasnevin Plains which is the opposite of the inferred regional groundwater direction (Loris, 2000). It is suggested that the abrupt change in topography caused by the terrace has created a local gradient in the groundwater table towards the Waipara River. Field observations of the Waipara River terraces show seepage on both sides of the river between Stringers Bridge and SH1.

Omihi Stream was sampled in the lower reaches before the Waipara River. From the start of sampling to June the $\delta^{18}O$ composition was quite constant (standard deviation 0.27, average $\delta^{18}O$ -7.62‰). Following the rainfall in early July the isotopic compositions of the stream became significantly more negative. Visual gauging suggests that in the early part of the year flow in the stream was fairly similar, and after the Winter rainfall flows were more variable. The isotopic composition of Omihi Stream between January and June is similar to many wells located in the North Waipara Hydrochemical zone. The source and recharge interpretations to the Omihi Stream are discussed in Section 3.2.6 and Section 4.4.1.2.

5.5.3 Comparative sites

5.5.3.1 Surface water sampling

The results from the three sampling runs on the major streams/ rivers in the study area are shown in Figure 5.7 Figure 5.8 and Figure 5.9.

The first of the sampling runs was conducted in mid to late April (Figure 5.7). To the North of the Waipara River sites had $\delta^{18}O$ values between -7.51‰ to -7.82‰ (Weka Creek -7.66‰ and Home Creek -7.51‰). This suggests these creeks are primarily sourced by rainfall and implies low storage in the upper catchment. In support, these streams have small total flows and often go dry in reaches during Summer (Lloyd, 2002). The Waipara River varied from -7.84‰ in the upper catchment to -8.34‰ at SH1 to -8.42‰ at the mouth. This downstream pattern may reflect inputs from a more negative (>8.18‰) groundwater system to the river. If so, this implies significant groundwater flow from the Glasnevin Plains and/ or Waipara Downs fans. Sites in the upper catchment of the Kowai River (NB) and Washpen Creek have similar values of -8.83‰ and -8.59‰ with -9.05‰ recorded at the confluence of these systems. The Kowai River at SH1 was dry. The Kowai River (SB) was -9.22‰, similar to Fox's Creek (-9.56‰) and M34/5821. The Ashley River seemed to be more positive downstream, reflecting coastal rainfall derived (-7.81‰) input into the river. Gauging data shows gains to the Ashley River before SH1 (Chater, 2004).

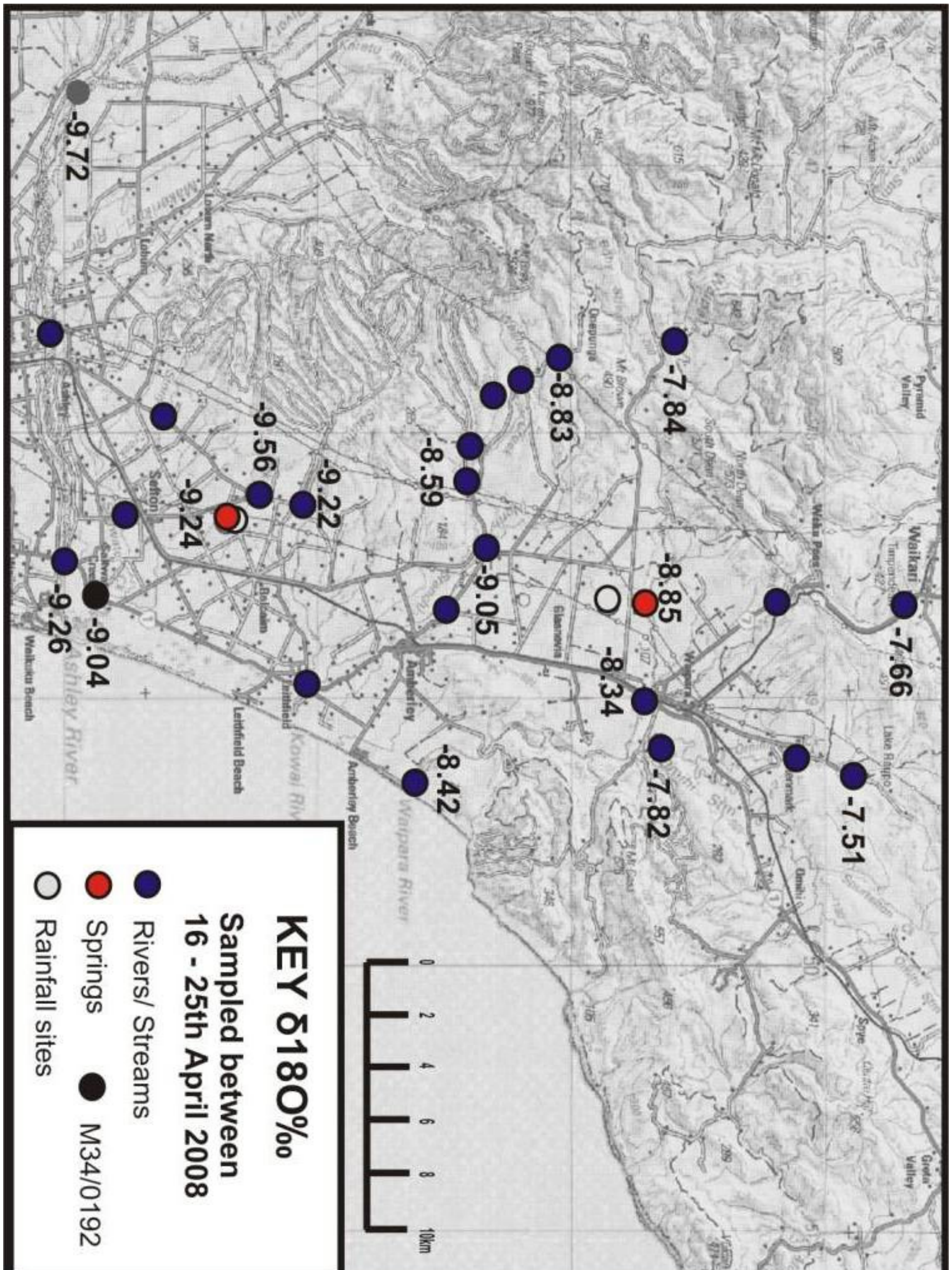

Figure 5.7 Results from the δ^{18}O sampled conducted in April 2008. Note rainfall sites are shown for reference but their results are not shown. The locations of all the surface water sites in the study area with isotopic data are shown. The springs are Bellbird spring and M34/5821.

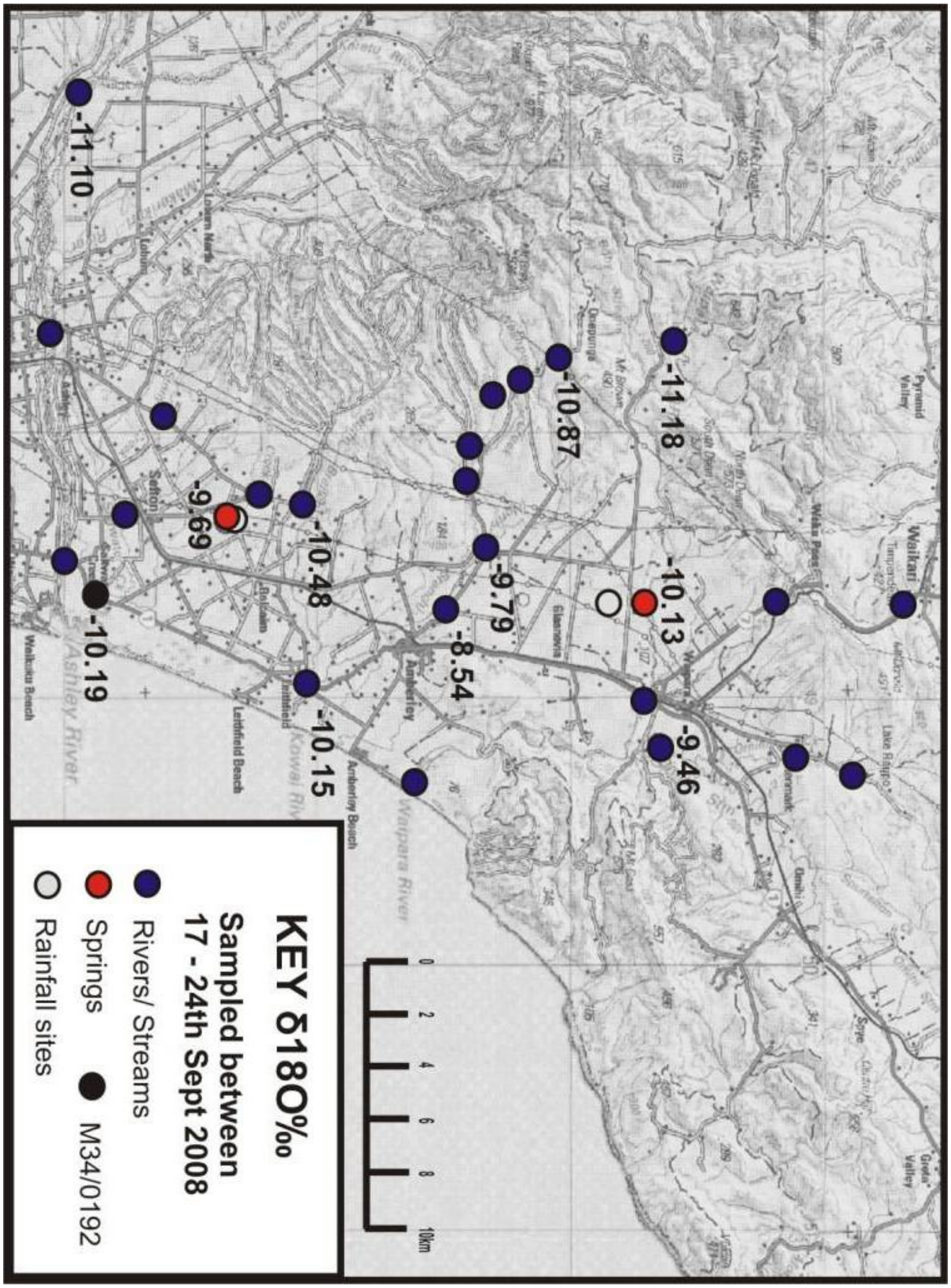

Figure 5.8 Results from the δ18O sampling conducted in September 2008. Note rainfall sites are shown for reference but their results are not shown. The locations of all the surface water sites in the study area with isotopic data are shown. The springs are Bellbird spring and M34/5821.

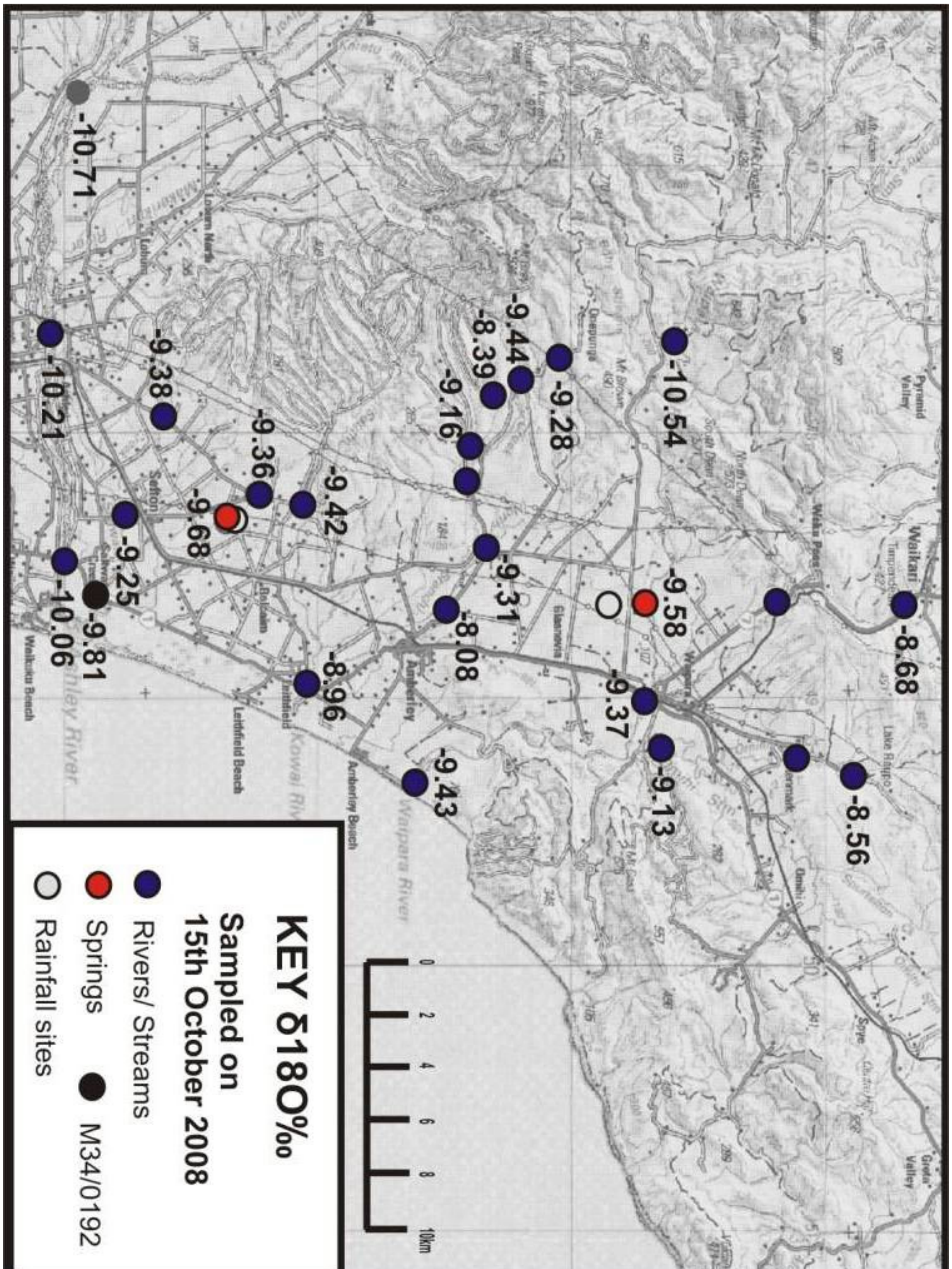

Figure 5.9 Results from the $\delta^{18}O$ sampling conducted in October 2008. Note rainfall sites are shown for reference but their results are not shown. The locations of all the surface water sites in the study area with isotopic data are shown. The springs are Bellbird spring and M34/5821.

A small sampling run was conducted in mid September (Figure 5.8) following the two large Winter rainfall events. At this time the Amberley Swamp (lake) had filled (refer to section 3.2.4). The purpose of the run was to see if there were any isotopic differences between discharge from the swamp and upstream flows.

In the upper catchment of the Kowai River (NB) $\delta^{18}O$ values were -9.79‰ and -10.87‰. The Kowai River (SB) had a similar $\delta^{18}O$ values. The discharge from the Amberley Swamp was -8.54‰. This and the chemical observations (section 4.4.2) show that the discharge from the swamp is derived from Waipara groundwater. The Kowai River at SH1 had a value of -10.15‰, reflecting the inputs from Kowai River (SB) and probably inflow from the small ephemeral streams.

The third surface water sampling run was conducted in October (Figure 5.9). North of the Waipara River all of the streams had become much more negative when compared to the April data (Figure 5.7). The Waipara River became progressively more positive downstream signifying inputs to the River from a more positive source (Omihi Stream and possibly groundwater). All the major tributaries of the Kowai River (NB) were sampled in October. Except Number One Creek, all the sites (including the confluence of these sites) had similar $\delta^{18}O$ values being between -9.16‰ to -9.44‰. Similar values were recorded at the Kowai River (SB) site. The Kowai River at SH1 was flowing and had a δ18O value of -8.96‰, more positive than sites in the Upper catchment. This reflects the input from the Amberley Swamp (-8.08‰), a greater proportion of flow from the North branch relative to the South branch and decreased flow into the system from small ephemeral streams (section 3.2.4).

Fox's Creek and M34/5821 had similar isotopic composition. There is little difference between the δ18O values determined from the April and October runs for these sites and the Kowai River (SB). Stormy Creek, one of the larger streams flowing from Ashley forest was sampled for the first time in October. It had a similar $\delta^{18}O$ value to the other stream draining the Ashley forest. The Ashley River became more positive downstream, similar to the pattern observed in April. Saltwater Creek δ18O value of -9.25‰ probably represents flow from both the Ashley River and inputs from the Downlands Hydrochemical zone (refer to section 4.4.4).

5.5.3.2 Groundwater sampling

Two groundwater sampling runs were conducted in April – May and September – October (Figure 5.10 and Figure 5.11). The isotopic composition of groundwater is often assumed to be relatively constant through time as an average of the recharge inputs.

For the most part the δ oxygen and hydrogen values for wells/springs between the two sampling period were fairly similar (75 and 25 percentile for Δ $\delta^{18}O$ 0.27‰ & -0.39‰ respectively, April minus October). However there were a number of predominately shallow wells where the October sampling showed a difference of more than 0.85‰ (N33/0064 9.1mbgl, M34/0670 24mbgl, M34/5818 6.5mbgl & N34/0365 5.7mbgl, Figure 5.10 and Figure 5.11).

In each case the wells were more negative in October than in April. N33/0064 in April had a stable isotopic signature similar to low altitude rainfall (<200m). In October this well had a $\delta^{18}O$ of -9.55‰ and δD of -65.0‰. This well is located within 20m from an ephemeral stream. This well either receives intermittent recharge from the stream or this signature may reflect the highly negative rainfall that fell in winter (Figure 5.3). M34/0670, M34/5818 and N34/0365 show similar temporal pattern however for M34/0670 it is interpreted the change in isotopic composition was due to flow from the Teviotdale hills (refer to section 4.4.2). M34/5818 is interpreted as being recharge by Southward flowing groundwater similar to the process recharging the Amberley Swamp (refer previous section and section 4.4.2). N34/0365 is interpreted to be connected to a nearby drain. This illustrates the limitation of using one off stable isotope sampling to categorise a dynamic system.

Recharge interpretations for wells and springs are based on the relationship shown in Figure 5.6 and Table 5.2. Generally sites with $\delta^{18}O$ <8.17‰ are interpreted to be recharged by low altitude rainfall or Weka, Home Creek/ Omihi Stream in the North Waipara Hydrochemical zone (see previous section & Lloyd, 2002). Sites recharged by low altitude rainfall tend to be shallow wells and are distributed throughout the study area.

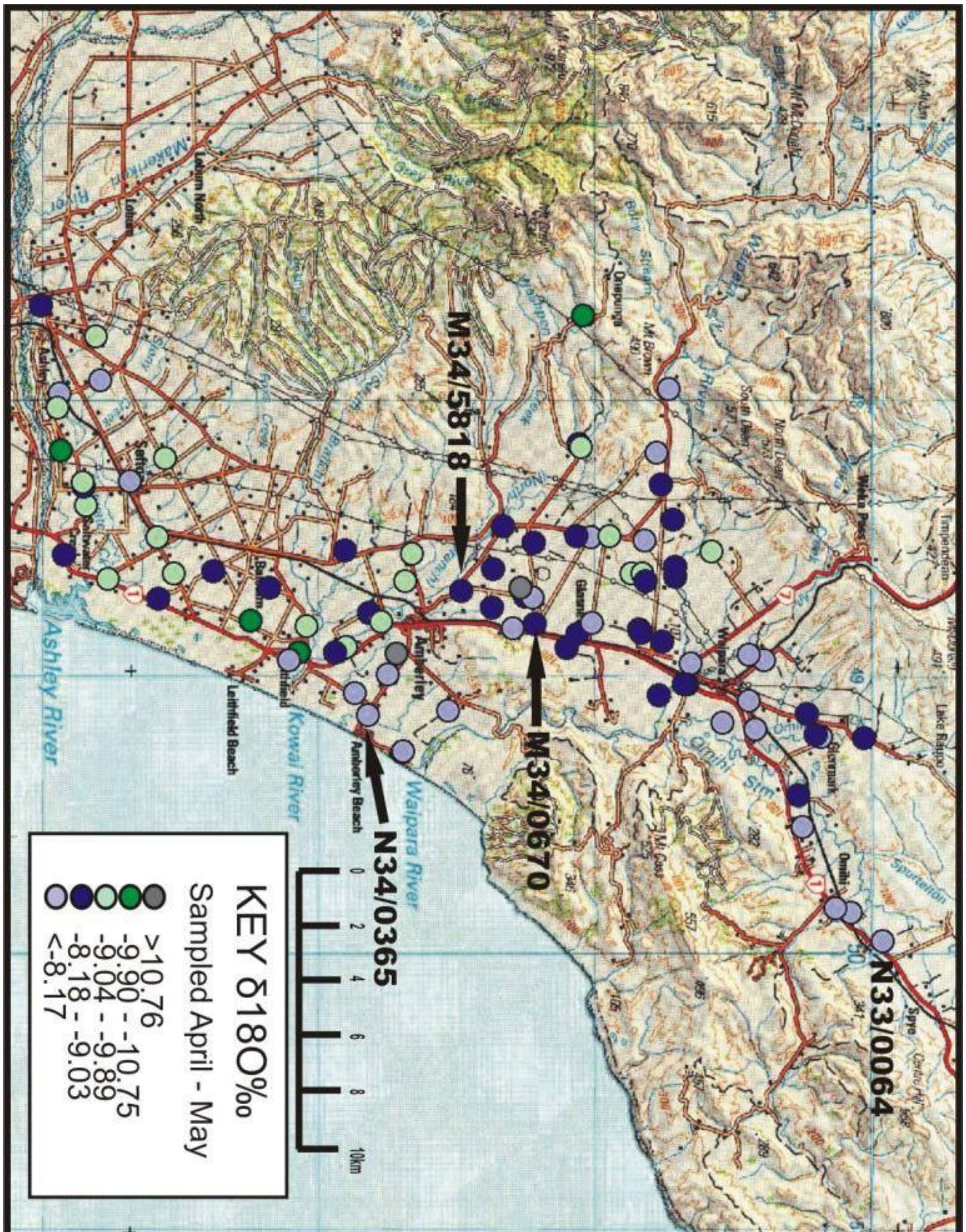

Figure 5.10 Results from the δ^{18}O sampling conducted in April - May 2008. Note δ^{18}O values above >10.76‰ are analytical errors.

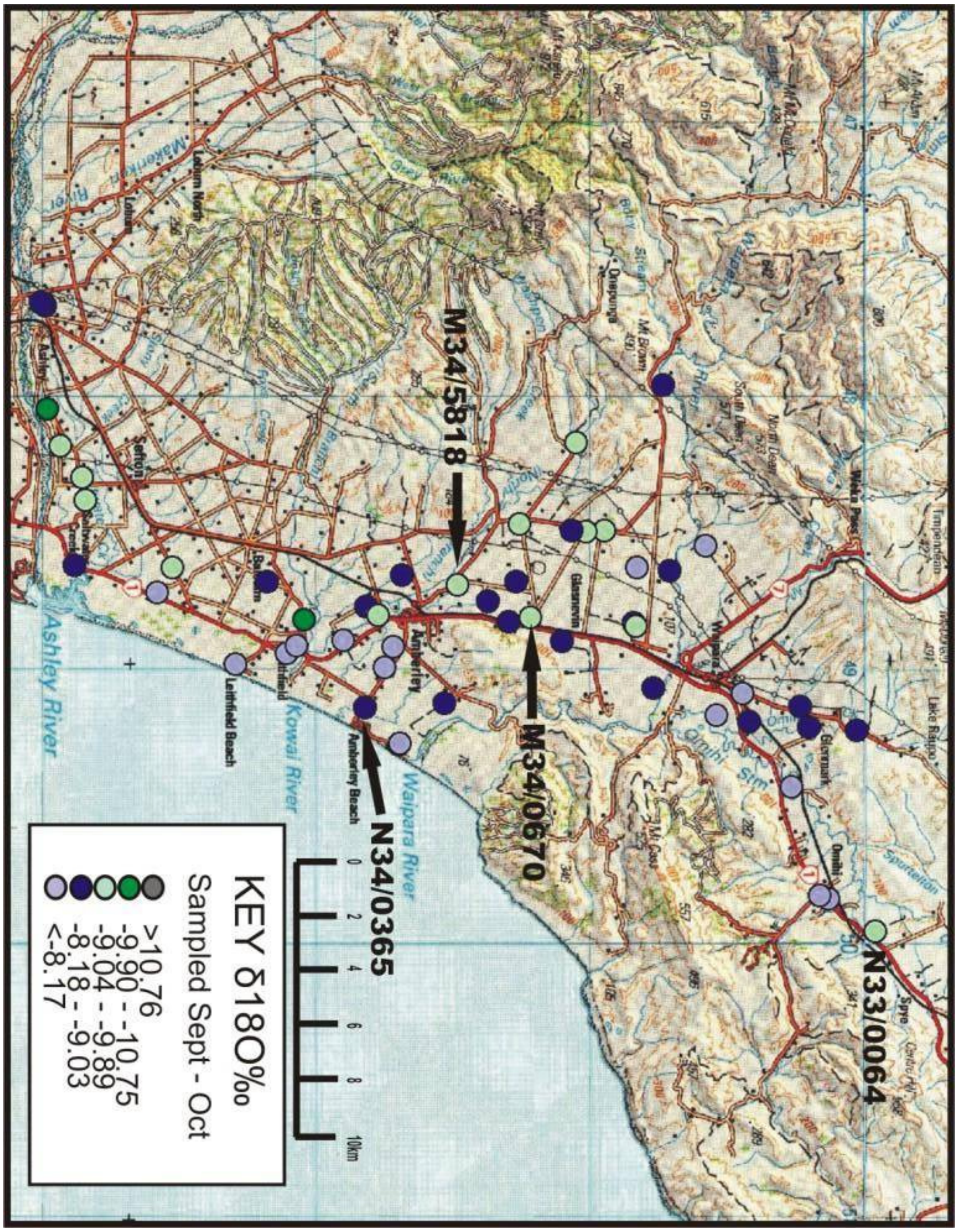

Figure 5.11 Results from the δ18O sampling conducted in September - October 2008.

In the area defined by the South Waipara Hydrochemical zone the $\delta^{18}O$ composition of the wells tend to be between -8.18‰ to -9.03‰ (this study and Loris, 2000). Lloyd (2002) proposed that the Waipara River did not lose significant water to the groundwater system where it crossed the basin. Chater's (2002) mean annual flow map showed small losses (total 40 L/s) from the river to the groundwater in this region but recent studies indicate that the Waipara River does not lose water in the Waipara Basin (Scarf, 2007). The locations of springs at the base of the Waipara

River terraces and stable isotopes data suggest the Waipara River is not a significant recharge source to the basin (section 3.2.7). Given there are few streams in this part of the basin it implies that the area South of the Waipara River is recharged by rainfall. This is supported by chemical data presented in section 4.4.2. It is therefore interpreted that the isotopic signature of these wells is an altitudinal effect, caused by rainfall falling on the margins (>200 masl) and flowing into the basin.

Wells South of Saltwater Creek tend to have $\delta^{18}O$ values >-9.04‰ indicating they are recharged predominately from the Ashley River. To estimate the proportions of recharge from a river and low altitude rainfall Stewart's (2006) mass balance equation was employed (Appendix 5c). All wells in this region coloured green (Figure 5.10 and Figure 5.11) were recharged solely from the Ashley River, whereas those coloured purple had ~20 to 35% contributions from low altitude rainfall.

Between the Kowai River (NB) and Saltwater Creek wells are interpreted to be recharged by rainfall or from water lost from surface water or both. Wells in Figure 5.10 and Figure 5.11 coloured green with $\delta^{18}O$ values >-9.04‰ are likely to be recharged from water lost from surface water sources. This is based on their proximity to ephemeral streams, the isotopic composition of those streams and water level data. The purple dots are interpreted to be recharged from both rainfall and surface water. This is supported by the proximity to surface water sources with known losses and water level data (section 3.5.1).

In the area between Amberley and Amberley Beach most of the wells are recharged by rainfall. However, the isotopic compositions, water levels and specific capacities of wells near the Waipara River suggest connection to a river. Chater (2002) recognised significant losses from the river below the middle gorge.

5.6 Groundwater dating

There are 19 wells and a spring in the study area with age data (Figure 5.13). Only one of this numbers is located in the Kowai zone. Six of these wells were dated using the ^{14}C dating method while the remainder have been analysed for Tritium, CFC's (Loris, 2000) and SF_6 in the case of the spring. Groundwater dating here is used to qualify and quantify recharge.

5.7 Methods

5.7.1 ^{14}C

^{14}C is a radioactive isotope produced naturally by the interaction of cosmic rays with atmospheric Nitrogen. ^{14}C oxidises to $^{14}CO_2$ which is consumed during photosynthesis and is assumed to be in equilibrium with atmospheric ^{14}C until the organism expires. The half life of ^{14}C in this document is taken as 5730 years[9]. The ^{14}C age dating method assumes that the initial concentrations are known (or can be estimated) and that all the ^{14}C loss is from radioactive decay alone. The equation is;

$$t = (1/\lambda).\ \mathrm{In}\ (a_o/a_t)$$

Where a_o the initial concentration, a_t is the ^{14}C activity after time t and λ is the decay constant.

For groundwater dating an addition term is required to take into account the mixing of waters of different ages, q (dilution factor).

$$t = (1/\lambda).\ \mathrm{In}\ (q.\ a_o/a_t)$$

q is often difficult to estimate but a number of methods have been developed and are summarized in Clark and Fritz (1997). The method used by GNS Rafter Radiocarbon Laboratory to estimate q is the ^{13}C method. The ^{13}C method assumes the water passing through the soil/ organic material at the time of recharge will adopt that ^{13}C signature, that being δ -25 ‰. Fossil carbonate sources are assumed to have a ^{13}C isotopic composition of δ -0 ‰. The mixing of fossil carbonate water with recharging waters will theoretically dilute the initial ^{13}C concentration. Therefore any deviation of the measured ^{13}C concentration at the time of sampling can be used to estimate q (Figure 5.14).

For groundwater the maximum reliable ages produced from this method is thought to be around 30 000 years (Clark and Fitz, 1997).

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[9] Half life of ^{14}C as used by the Rafter Radiocarbon Laboratory, whereas Libby's half life is 5568 years

5.7.2 Tritium

Tritium is a radioactive isotope of Hydrogen with a half life of 12.4 years. Tritium is naturally produced by cosmic rays interacting with atmospheric ^{14}N. In the mid 1950's vast amounts of Tritium were produced as a result of nuclear testing. The production of Tritium peaked in the mid 1960's (Clark and Fitz, 1997) and has subsequently declined to background levels by about the mid 1980's (Figure 5.12). Anthropogenic and natural Tritium enters the groundwater system via precipitation or river recharge. Tritium has been measured in rainwater near Wellington since 1960 (Taylor et al, 1989). Knowing the decay rate, by estimating the initial Tritium concentration and determining the Tritium concentration after sampling allows the age to be determined.

Because of the tritium peak and the time that has elapsed since it peaked; up to three ages are possible under some circumstances. Ambiguities are resolved by multiple samples or by sampling using other techniques. The main advantage in using Tritium is that it is only removed from the system by radioactive decay and there are few source of contamination.

5.7.3 CFC's and SF^6

CFC's are stable organic compounds created initially for refrigeration but now have numerous industrial uses (Plummer and Busenberg, 2000). The concentration of these compounds has increased significantly from 1960's through to 1990 (Figure 5.12). CFC's have had an adverse effect on the ozone layer which has led to efforts to reduce their use and as a result their concentrations have tapered off (CFC-12) or started to decline (CFC-11) since the early 1990's. SF_6 is a man made gas used in the power industry. SF_6 concentrations have increased since the 1970's through to the present (Figure 5.12).

Similar to Tritium, CFC's and SF_6 are used to date water because they enter the groundwater system (this time as a dissolved gas) at a concentration that can be estimated. Knowing the concentration after sampling can provide a age. However, because CFC's are stable and atmospheric concentrations since 1990's have declined or stabilized, water recharged after this period can be ambiguous. Furthermore CFC's and SF_6 are dissolved gas and do not travel at the same speed as water resulting in a "time lag" when the unsaturated thickness is greater than >5 – 10m (Cook and Solomon, 1995. Busenberg and Plummer, 1999. Plummer and Busenberg, 2000). CFC can also be affected by reduced groundwater conditions and contamination. To determine CFC's and SF_6 recharge temperatures and excess air need to be estimated.

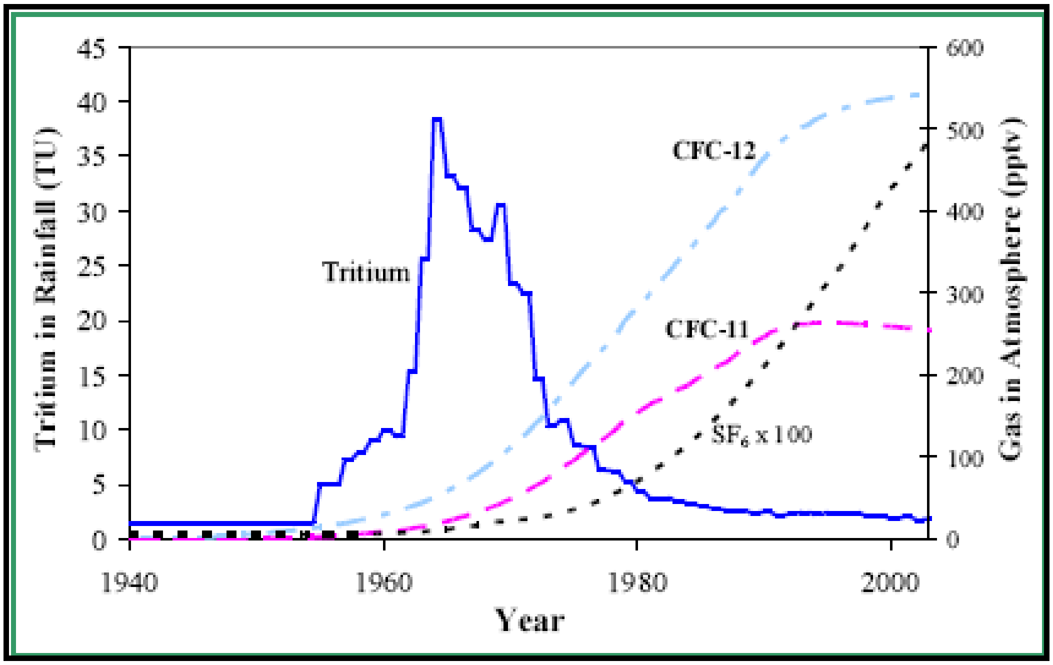

Figure 5.12 Tritium concentration in rainfall at Kaitoke, New Zealand and CFC and SF6 concentrations in the Southern Hemisphere atmosphere (from Stewart and Thomas, 2002).

5.7.4 Sampling procedures

Sampling procedures for purging wells are the same as described in section 4.2.2. For ^{14}C, the sample was collected in a 500ml glass container with a nylon insert fitted in the cap which forces out air as the cap is tightened. The container was flushed several times with water from the well, filled, allowed to overflow and then the cap fitted. The samples were sent to the laboratory within a couple of days of sampling.

For sampling of the spring (N34/0165) a small hole was hand dug near the vent of the spring with water removed from this hole using a peristaltic pump. For the Tritium sample one litre was collected in a Nagene bottle. The bottle was flushed several times and filled slowly from the bottom using the nylon tube from the pump. CFC's were collected in a 125ml plastic bottle inside a bucket. A nylon tube was inserted into the bottle and slowly filled until overflowing. After several litres of water had passed through the bottle the cap was fitted (submerged beneath the water line). The bottles were filled and checked to minimize the amount of air bubbles within the sample. SF_6 was collected in a 1 litre glass bottle. The bottle was filled in a similar manner as described for the CFC's without being contained within a bucket. The samples were sent that evening to GNS laboratory in Wellington to be analyzed.

5.8 Results and discussion

5.8.1 ^{14}C

^{14}C age dating was conducted on six relatively deep wells (>60 mbgl, Table 5.4 and Figure 5.13). Two samples were collected by John Weeber in February and May 2007. A further four samples were collected by Phil Abraham, assisted by the author between July and December 2007.

Table 5.4 $\delta^{18}O$ of water, ^{13}C, ^{14}C concentrations of dissolved inorganic carbon and age determinations.

Date sampled	Bore ID	$\delta^{18}O$	$\delta^{13}C$	$\delta^{14}C$ (pmC)	TDIC ($mmol.kg^{-1}$)	Age (years)*	Error*
10-Jul-07	M34/0340	-7.64	-20.8	57.65 ± 0.24	2.94	2700 - 4300	
10-Jul-07	M34/5540	-8.18	-17.7	59.53 ± 0.25	1.72	1300 - 4300	
5-Dec-07	M34/5707	-8.52	-18.7	32.09 ± 0.19	2.13	7000 - 9400	
28-Feb-07	N34/0106	NS	-17.3	48.55 ± 0.22	2.41	1300	± 300
28-Feb-07	N34/0131	NS	-10.6	15.96 ± 0.12	3.63	7100	± 1000
10-Jul-07	N34/0139	-8.47	-12.3	5.79 ± 0.09	3.36	17800 - 23500	

The presentation of ages and errors from the Rafter Radiocarbon Laboratory were different for the sampling conducted by J Weeber and that conducted for this study. The first two ages were presented as age ± analytical error whereas the final four ages where presented as a range. One end of the age range was calculated by using an 0% dilution factor, the other by using the dilution factor calculated from the ^{13}C method.

Figure 5.14 is a plot of percent modern carbon (pMC) against $\delta^{13}C$. Illustrated on the graph are two end members; groundwater thoroughly mixed with a fossil carbonate source (pMC 0, $\delta^{13}C$ 0‰), groundwater with all ^{14}C consumed by radioactive decay only (pMC 0, $\delta^{13}C$ -25‰). All the samples plotted have $\delta^{13}C$ less than -25‰ suggesting they have all been mixed with a fossil carbonate source. N34/0131 and

N34/0139 have had the most interaction with fossil carbonate which is in agreement with the chemical data (section 4.4.1).

Shown in Figure 5.15 is Total Dissolved Inorganic Carbon (TDIC) plotted against $\delta^{13}C$. Three of the wells (M34/0340, M34/5707 and M34/5540) have similar concentrations of these determinants and trend away from the assumed initial $\delta^{13}C$ concentration. N34/0106, N34/0139 and N34/0131 show a trend towards $\delta^{13}C$ 0‰ suggesting interaction with fossil carbonate.

How much confidence can we put in these results? Bore log data and chemical data (section 4.4) suggests that limestone clast content in the basin fill deceases Southward. Figure 5.13 shows that show of oldest ages determined from this ^{14}C dating method occur in the North of the basin. Furthermore some soils in the Omihi valley contain calcium carbonate horizons (per com. P Tonkin, 2008). However N34/0106, N34/0131 and N34/0139 had only background concentrations of Tritium when sampled by Loris (2000). Wells at similar depths South of the Waipara River still had a recorded age >1000 years. Therefore while the author has some doubts about the errors involved in this method, it still indicates older mean residence ages (>thousand years) than have been previously recognised.

Nicol et al (1994), Loris (2000) and Finnemore (2004) found that within the Waipara Basin there are a number of emerging structures. Armstrong (2000) suggested that emerging structures in the Culverden basin had the potential to create sub basins. It is hypothesized that due to the geometry of the basin (section 2.5.2), the emergence of these structures within the basin and the low transmittivity of the basin fill, deep groundwater flow is being obstructed resulting in >1000 year old water at depth. In support of this proposition, plotting all the age data against depth results in a reasonable logarithmic trend (R^2 = 0.53). A reasonable logarithmic trend would be expected if you had groundwater ponding at depth. Interestingly, when the deepest well in this data set (M34/5540) is excluded and the data replotted, the coefficient of determinant increases to 0.76. This well is likely to be in the Kowai Formation while the remainder are in the Teviotdale, Omihi/ Canterbury Formations. This may suggest disconnection between the Pliocene and Pleistocene formational aquifers.

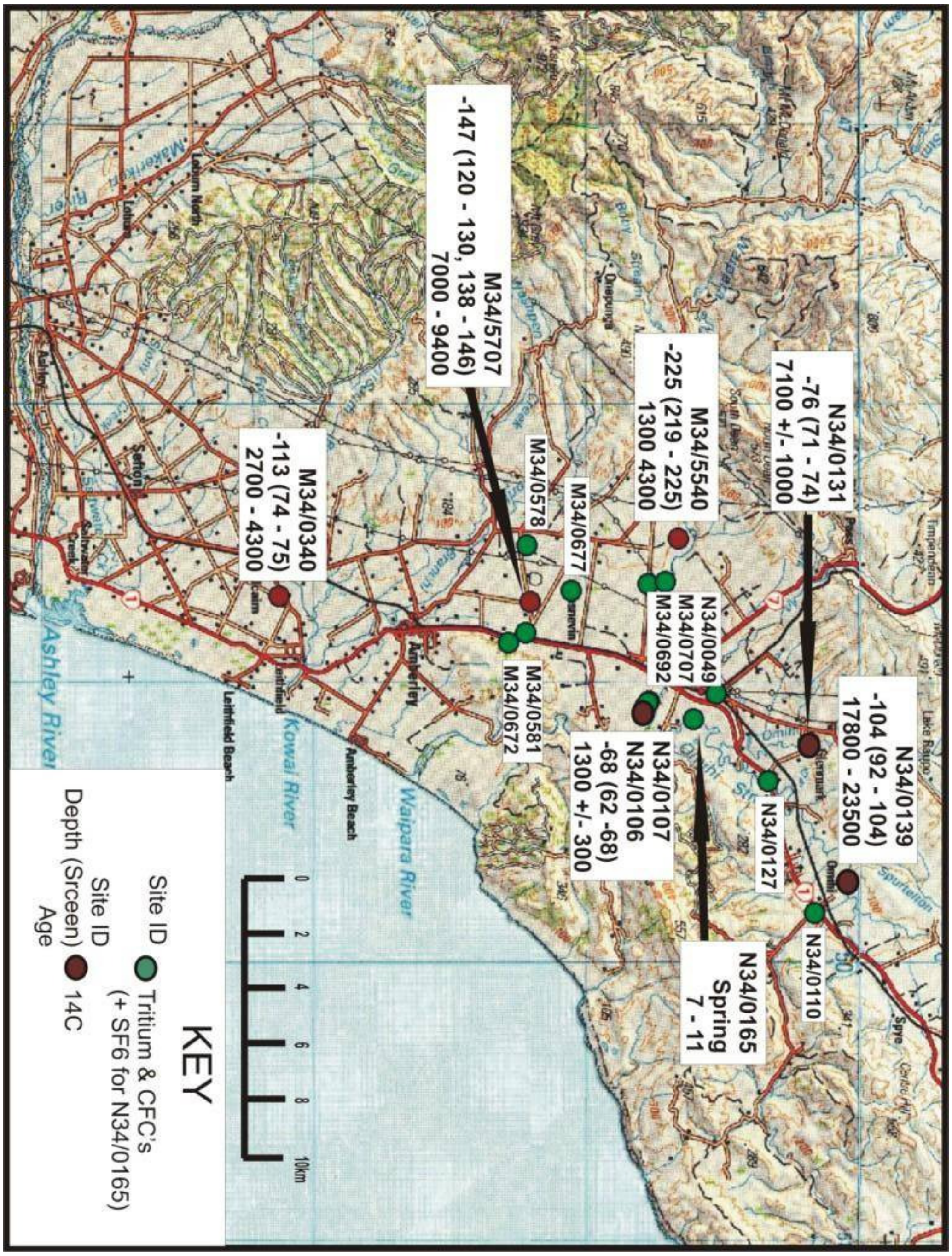

Figure 5.13 Map showing the spatial distribution of wells/springs in the study area with age data. Only age data results from this study are shown. The results from the remainder of the sites are discussed in Loris (2000).

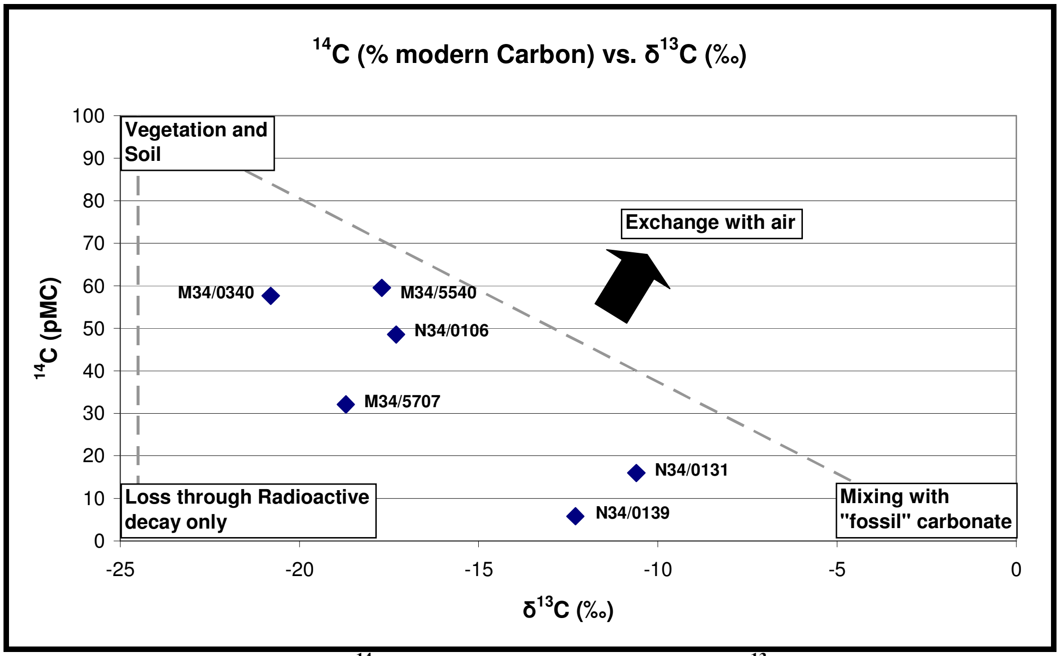

Figure 5.14 Scatter plot showing ^{14}C percent modern carbon against $\delta^{13}C$. Plotted are all the wells in the study area with ^{14}C age determinations data.

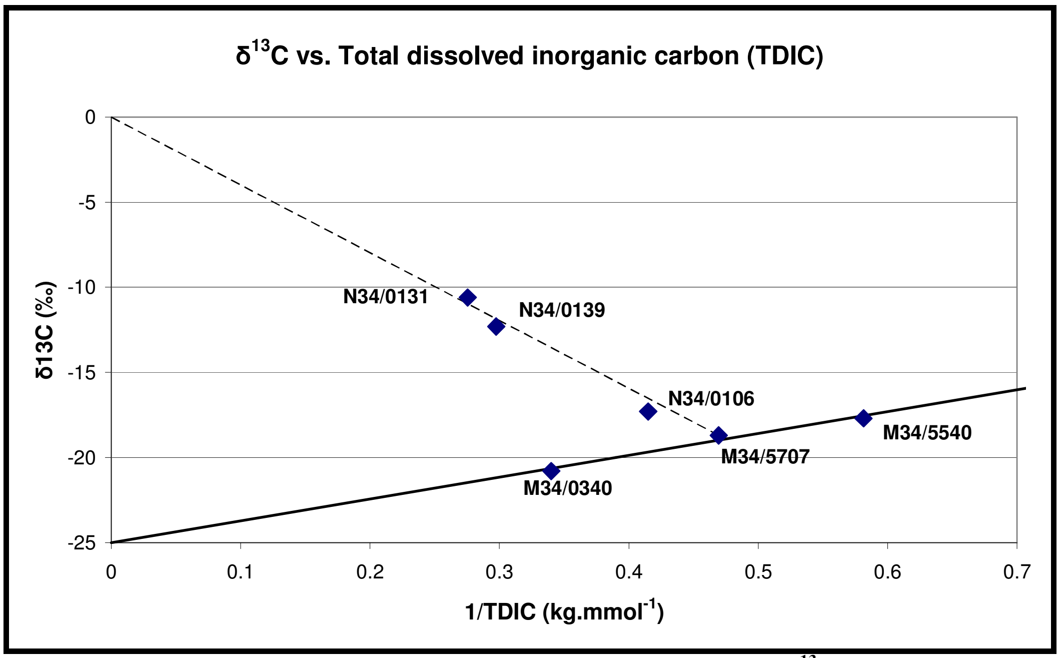

Figure 5.15 Scatter plot showing total dissolved inorganic carbon against $\delta^{13}C$. Plotted are all the wells in the study area with ^{14}C age determination data.

5.8.2 Spring dating

The results from sampling of N34/0165 are shown in Table 5.5 and Table 5.6. The results are somewhat ambiguous in that mean ages from the different techniques give different results. Two different mixing models (EPM) were produced by the Rafter laboratory to fit the data.

The geomorphic interpretations and chemistry data (section 4.4.1) suggest this spring is recharged from the North and Northwest. This suggests convergence of flow line and therefore a 100% mixing model would be appropriate. Given that the Tritium and SF_6 data agree, that CFC's may have been affected by microbial degradation and that CFC's provide unreliable ages for the water recharging after 1990, an men age of 7 – 11 year is tentatively adopted here.

Table 5.5 Calculated atmospheric partial pressures and measured Tritium concentrations.

Recharge Temp. ºC	Excess air	CFC – 11 ppt	CFC – 12 ppt	SF_6 ppt	Tritium TU
8.6 ± 1.6	2.7 ± 1.0	54.3 ± 5.1	316.3 ± 29.9	4.03 ± 0.46	1.70 ± 0.05

Table 5.6 Mean ages for Tritium, CFC's and SF6 and calculated youg fraction (In brackets) using 30 and 100% exponential piston flow model.

Exponential mixed flow (EPM) model mean age (years)				
EPM %	CFC-11	CFC-12	SF_6	Tritium
100	130 (+39, -26)	32 (+14, -10)	11 (+8, -5.5)	7 (+5, -2)
30	43 (+2, -2)	27 (+4, -4)	9 (+5, -4)	35 (+3, -2)

5.9 Age data recharge estimates

Recharge rates have been estimated from Loris (2000) Tritium and CFC's data using the methodology of Delin et al (2006)(Table 5.7). Whereby;

$$R = \varphi V_v.$$

R is the estimated recharge rate in mm/year, φ is an estimate of the average saturated zone porosity and V_v is vertical velocity at the water table. V_v is calculated from;

$$V_v = z/age$$

Where z is depth to the middle of the screen in mm and age is the mean residence time for recharging water in years.

This method assumes that recharge to the well is by vertical drainage. It is probable that deeper wells are receiving recharge from a much larger distance up gradient from the site (Delin et al, 2006). The average recharge rate in Table 5.7 is similar to that Lloyd (2002) but half that of Aqualinc (2005).

Table 5.7 Recharge rate calculations using age data from Loris (2000) using the methodology of Delin et al (2006).

Site ID	z (mm bgl)	Recommended age	V_v	φ	R (mm/yr)
N34/0107	27250	55	495.45	0.1	50
M34/0707	31150	45	692.22	0.1	69
N34/0127	23250	47#	494.68	0.1	49
M34/0672	34700	48	722.92	0.1	72
M34/0581	26800	32	837.50	0.1	84
M34/0692	26250	38	690.79	0.1	69
N34/0049 *	33400	22	1518.18	0.1	152
M34/0677 *	10800	12	900.00	0.1	90
				Range	102
				Std Dev	32
				Average	**79**
* = no screen data. Assumes that the screen is one metre above the bottom of the well, as it is unlikely to be at the very bottom of the well					
# = used available data, not recommended age from Loris (2000)					

5.10 Chapter summary

Stable isotopes of water have been used to determine recharge to sites in the study area. Four long term average rainfall sites $\delta^{18}O$ on the Canterbury Plains have been used to establish a relationship between $\Delta\ \delta^{18}O$ and Δ in altitude (lapse rate -0.49‰/ 100m). This has been used to predict the $\delta^{18}O$ concentration at various altitudes which compared well to East Coast $\delta^{18}O$ data from Chamberlain et al (1999).

Just under a years worth of $\delta^{18}O$ and δD have been collected from the four major rivers and stream in the area, plus two springs and a flowing artesian well (M34/0192). This data combined with data collected from other sources (Taylor et al, 1989) have allowed average isotopic compositions to be calculated. This data was compared against data collected from other wells, springs and surface water sites to determine recharge, flow dynamics and estimates of proportion of recharge between two sources.

^{14}C age data has been collected from six relatively deep wells mainly in the Waipara Basin. While there is some doubt about the error associated with these ages, they do suggest that there is significant retardation to flow in the basin, interpreted to caused by low transmissive sediments and the impound caused emerging structures.

Using data from Loris (2000) and the methodology of Delin et al (2006) recharge rate have been estimated. The average of these recharge rate is similar to that produced by Lloyd (2002) but half that of Aqualinc (2005).

6 Chapter six: Conceptual model and water balance

6.1 Introduction

The purpose of this chapter is to develop a coherent conceptual model of groundwater recharge and flow in the study area. The conceptual model is based on the work of Toth (1963) and Freeze and Witherspoon (1967) who emphasised the role of topography in groundwater systems (i.e. gravity driven). An additional conceptual model is proposed to explain the influence tectonic uplift and loess deposition has on potential recharge over time. The chapter concludes with the presentation of a simple water budget and a brief discussion of its implications.

6.2 Theoretical background

Early workers noted that the water table was often a subtle replica of the ground surface (Hubbert, 1940). This observation led Toth (1963) to investigate the role of topography in groundwater systems. He found that where there was little topography (i.e. prairies) "regional flow systems" could develop, whereas when the landscape was dominated by closely spaced hills "local flow systems" developed between the drainage divides.

Freeze and Witherspoon (1967) expanding on Toth's (1963) model, confirmed topography as a critical factor in groundwater movement. They further established that the distribution of the hydraulic conductivities (stratigraphy), water table configuration and ratio of basin depth to width were important factors. These concepts are still valid and are being used by numerous workers, with varied research interests (Winter, 1999. Fetter, 2001. Sophocleous, 2002. Schilling, 2009).

6.3 Conceptual hydrogeological model

6.3.1 Waipara zone

This conceptual hydrogeological model has been invoked to explain the distribution of the hydrogen and oxygen stable isotopes data, water chemistry data, surface water interpretations presented by Lloyd (2002), Chater (2002, 2003) and Scarf (2007), geomorphic interpretations and field observations from this study and groundwater dating (Loris, 2000 and this study). This conceptual hydrogeological model is an attempt to build on the earlier work of Loris (2000) and Lloyd (2002).

Figure 6.1 Photography of a highly porous member of the Mount Brown Formation near the North Deans. Photograph taken at Grid ref M34:813 – 965.

The Waipara Basin is a syncline, plunging to the South (Loris, 2000). On the Eastern and Western margins there are active thrust/ reverse faults exposing basement in the cores of Anticlines. Wilson (1963), Nicol et al, (1994), Loris (2000) and Finnemore (2004) have shown that there are active structures within the basin that have little surface expression. It is interpreted that along the margins of the Waipara Basin and the Omihi valley, alluvial fans have formed and in places have built out into the basin (section 2.2). The majority of the basin fill consists of three gravel formations thought to be formed during major climatically driven aggradation events, punctuated by periods of tectonically (Nicol and Campbell, 2001, Campbell et al, 2003) and/or climatically driven fluvial incision (section 2.2). The Tertiary cover sediments are composed of soft to indurated sandstones, mudstones and limestones that contain potential aquifers (Figure 6.1, section 3.2.7. McCulloch, 1981. Loris, 2000 and Lloyd, 2002).

It has been shown from limited aquifer tests conducted within the Waipara Basin that the values for transmitivities of gravel formations are low (maximum value 490 m^2/day) when compared to an average from tests conducted on the plains (3199 m^2/day). From field observations it appears that there is a grey gravel lag unit at the surface near active channels that is likely highly permeable but with a thickness of less than 5m (most likely unconfined). It is assumed here to be laterally continuous on the basin floor. The Canterbury and Omihi Formation is estimated to be 5 – 30m thick (Wilson, 1963) and tends to be semi-confined to confined with low transmitivities (<150 m^2/day). The Teviotdale Formation has a minimum thickness of 25m based on the height of the top of the Mound above the Waipara River. Wilson (1963) estimated a maximum thickness of 100m. This unit may be a composite containing more than one gravel package separated by depositional breaks as seen below the Mound. The Teviotdale Formation tends to be semi-confined to confined. Transmitivities for this formation have been calculated as high as 490 m^2/day but typically less than 170 m^2/day. Browne and Field (1985) suggested a maximum thickness of 650m for the Kowai Formation. It is known however that the Kowai Formation has been partly removed in the Omihi valley due to uplift and subsequent erosion along the Omihi Fault system (Finnemore, 2004). N34/0351 (-220m depth) resulted in transmitivities of 19 m^2/day and was semi-confined. The data shown in section 3.4.1 show a general decrease in specific capacity with depth. It is argued that this is caused by weathering of the gravel formations and due to the accumulation of silt and clay within the pore space transported by groundwater (Davey, 2006).

It is proposed that Waipara Basin receives recharge from rainfall falling both onto the floor and margins of the basin. Slopes derived from a 15m digital terrain model show that generally the Kowai Formation lies beneath slopes that are inclined at 7 - 15º, Teviotdale Formation havs slopes between 3 - 7º and the Canterbury and Omihi Formation is found beneath slopes of <3º. Tertiary Formations along the margins are inclined at slopes generally greater than 15º. A number of the surfaces on these slopes are covered by anything from a single thin loess sheet to multiple loess sheets (per com. P Almond, 2008). Given this and the hydraulic properties of the gravel formations, it is proposed that when rainfall falls on the Kowai Formation a small proportion infiltrates into the soil and the remainder runs offs or moves as interflow into the basin (Lloyd, 2002). Where interflow is "*lateral movement of water in the* *vadose zone during and immediately after a precipitation event*" (Fetter, 2001, page 556). This runoff and interflow is infiltrated into those younger gravel formations further down slope or diverted into stream channels (Figure 6.2). Lloyd (2002) showed that most streams in the Waipara Basin are ephemeral suggesting that they flow over a subsurface that readily accepts water. The Waipara River is interpreted to not to lose any water in the Waipara Basin (Loris, 2000, Lloyd, 2002, Scarf, 2007). It is suggested that this is due to the low hydraulic properties of the Teviotdale Formation into which the river has cut down and flows over. Alternatively this may be caused by abrupt down cutting (Nicol and Campbell, 2001) lowering the Waipara River beneath the water table.

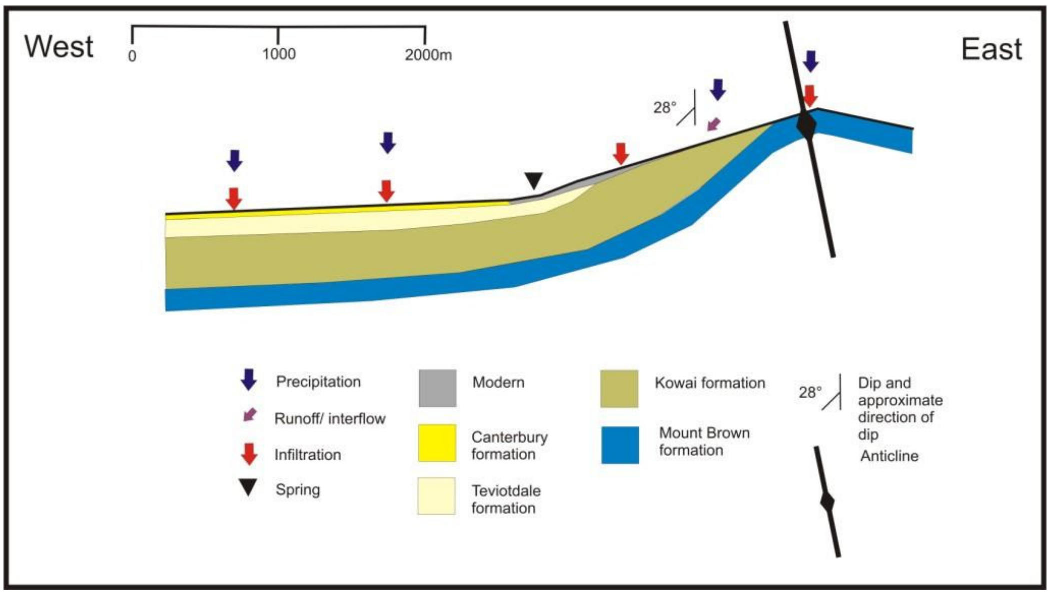

Figure 6.2 Interpretative geological cross section through the Teviotdale hills showing the major stratigraphic formations and recharge interpretations. The cross section is drawn with no vertical exaggeration.

Groundwater chemistry and piezometric surveys (Loris, 2000) suggest that regional groundwater flow direction is Southwards toward Amberley. However, geomorphic, geophysical, structural (Nicol et al. 1994) observations and groundwater dating suggests that groundwater movement at depth is hampered because of the emergence of tectonic structures within the alluvial fill. For example the Broomfield Fault is clearly acting as a barrier to shallow groundwater (section 3.2.4). Armstrong (2000) hypothesised that emerging structures within the basin fill have the potential to create groundwater compartments presumably by folding of the hydrogeological basement.

Some Tertiary formations are potential aquifers (Loris, 2000, Lloyd, 2002 and section 3.2.7) Near the Teviotdale recorder on the Waipara River there are significant losses (Chater, 2002) coinciding with exposures of Tertiary sediments at the surface. Loris (2000) and this study showed that spring flow is occurring from some of these formations particularly from the limestone members in the Mount Brown Formation. It is likely that these formations are receiving recharge from rainfall in addition to river recharge (section 3.2.7). Whereas Lloyd (2002) believes that the gravel formations are being recharged from water moving vertically up faults from the Tertiary formations, here it is argued that the groundwater chemistry results could be explained simply by the presence of Tertiary clasts (limestone etc.) within the basin fill and that significant deformation would have to occur before sediments of varying hydraulic properties are juxtaposed against each other (Yousif, 1987 and Nicol et al, 1994). Furthermore this degree of deformation would likely to be readily obvious from the surface. Nicol et al (1994) noted that significant deformation in this region is likely to be taken up in the form of folding.

6.3.2 Kowai zone

This conceptual hydrogeological model has been invoked to explain the distribution of the hydrogen and oxygen stable isotopes data, water chemistry data, water level observations, surface water interpretations, geomorphic interpretations and field observations from this study.

The Kowai zone is located on the gently Southward sloping limb of the Kowai Anticline. Near the Kowai Anticline there are limited outcrops of Tertiary sediments however the Kowai Formation outcrops extensively in the Ashley forest area (Hoolihan, 1978, Browne and Field, 1985). Geomorphic mapping and morphometric analysis showed that the landscape is stepped. This is interpreted to represent packages of sediment (and cover deposits) formed during distinct periods and subsequently preserved due to tectonic uplift and changes in the sea level. The lowest levels are likely to be equivalent to Brown and Wilson (1988) Springston – Bromley formations. However there are limited aquifer test data and bore logs in this region to estimate the spatial extent of these formations and their hydraulic properties.

The higher surfaces where Kowai Formation is exposed at the surface, is highly dissected, with slopes varying from 7 – 35º where the pattern of consequent rivers and streams flowing down the flanks of the emerging Anticline, have formed V shaped valleys. The valley floors are likely to be lined with modern fluvial and alluvial deposits. It is interpreted that only a proportion of rainfall infiltrates into the Kowai Formation. It is likely that a proportion of the rainfall is directed into the valleys as interflow and runoff. This interpretation is supported by the limited visual and instantaneous gaugings of Kowai River (SB), Fox's Creek and Stony Creek which have flow in their upper catchments most of the year. These streams lose all their water as flow onto the downlands. Field observations and the soil survey showed that loess was absent in the channels of the major river and thinned in the channels of minor streams.

Thorley and Ettema (2007) conducted limited infiltration tests on loess in South Canterbury and showed that ground-based recharge was severely impeded. This is also likely for the areas in the Kowai zone which are blanketed by loess. Water level data (section 3.5.1) shows that shallow wells on the downlands distant from any stream responded quickly to the significant rainfall events that occurred in 2008. This indicates that there is some direct rainfall recharge entering the system, perhaps through macropore flow (Williams and Allman, 1969, Beven and Germann, 1982), or where loess is thin or absent in valleys.

Water levels (section 3.5.1), chemistry (section 4.4.1) and isotopic data (section 5.4.3) clearly show the Saltwater Creek area is recharged from the Ashley River to the South and from the Southeasterly flowing groundwater emanating from the downlands.

6.3.3 Downlands

Shown in Figure 6.3 is a conceptual hydrogeological model of groundwater recharge to the downlands through time. Figure 6.3 attempts to trace the path of a hypothetical fluvial gravel unit and potential recharge rates to that hypothetical unit from deposition to some point in the future where it is at some elevation (>50 masl) and covered by multiple loess sheets. The conceptual model assumes constant uplift, that constant uplift equates to a surface that continually ascends through time, that continued uplift has outpaced rises in sea level, that loess has accumulated through time (though at varying rates and with minimal erosion) and that major rivers have always been losing water to groundwater in their lower reaches.

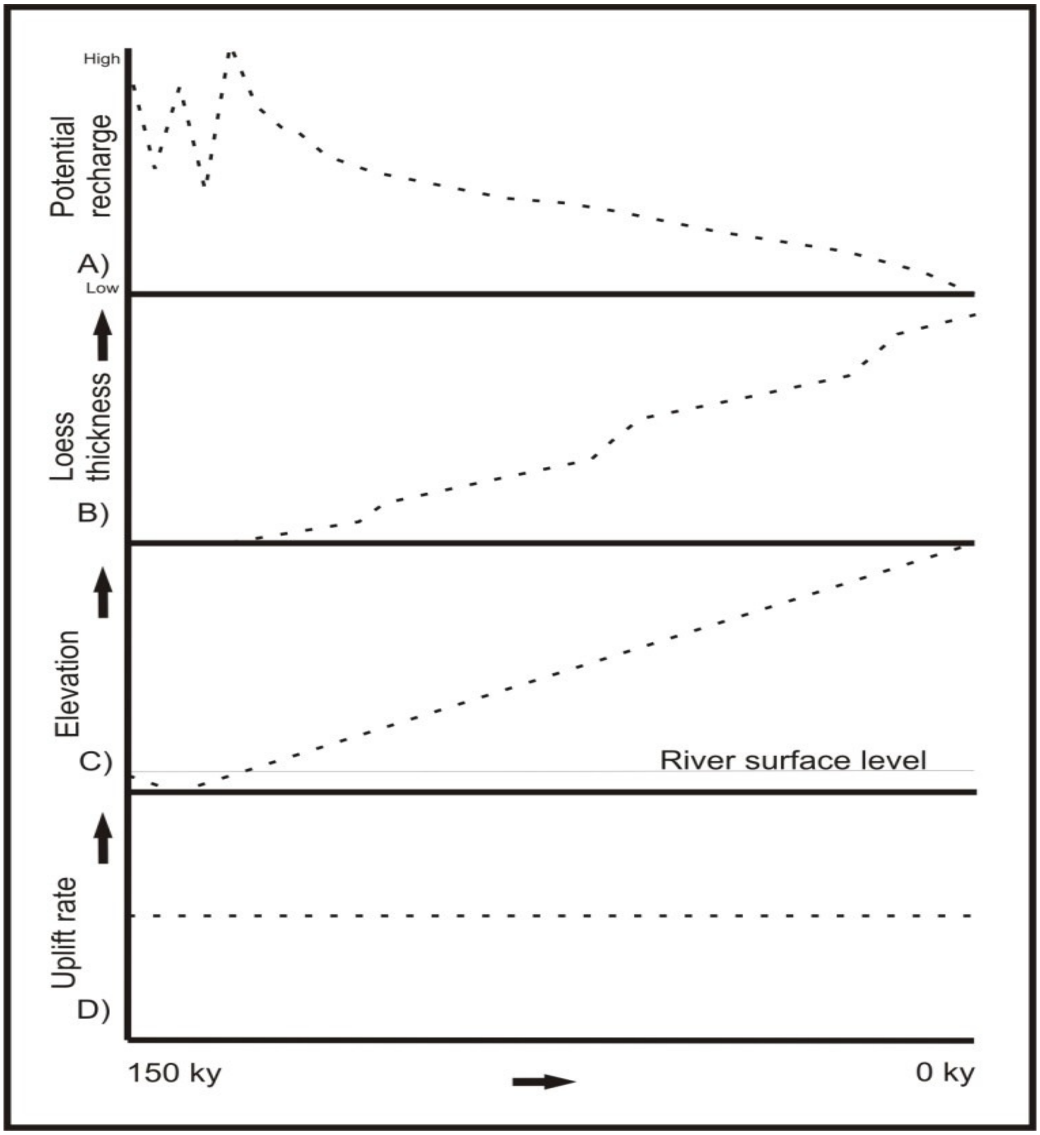

Figure 6.3 Conceptual hydrogeological model showing the impact of tectonic uplift, loess accumulation and fluvial systems on groundwater recharge through time to a hypothetical gravel unit.

This hypothetical gravel unit is deposited by the river (~150 ky ago), at some elevation above sea level, on a piedmont during an aggradational event. While the river is actively aggrading there is potential for this hypothetical gravel unit to be initially buried by subsequent aggradation. During major aggradation periods it is likely that rivers will avulse to a different part of the fan. Potential recharge rates are likely to be affected by river avulsion because water lost from the river is likely to recharge sediments relatively close (within several kilometres) distances to the channel. At some point in time this hypothetical unit is uplifted above the active channel which allows loess to be preserved. With time, the hypothetical unit accumulates a significant thickness of loess and is raised well above the active channels of major rivers.

It is argued that the accumulation of loess and removal of potential river recharge will significantly change the potential recharge rates to the hypothetical gravel unit. By continually uplifting the surface it precludes recharge from major rivers. Newly created topography will eventually affect the rainfall patterns (orographic effects (Lloyd, 2002)) and create new drainage networks, though with much smaller catchments than the previous surface water regime. The accumulation of loess on the hypothetical unit is likely to restrict the amount of rain water draining to groundwater. The net effect is that potential recharge rates through the land surface will decrease with time.

6.4 Water balance

Hydrological mass balance is a common technique used by hydrologists and hydrogeologists to estimate the quantity of water within a system (Scanlon et al, 2002). Mass balances for groundwater systems are calculated from the equation;

$$\text{INPUTS - OUTPUTS} = \Delta\ \text{STOARGE}$$

Examples of inputs to a system are rainfall, river recharge, groundwater inflow etc. Examples of outputs to a system are actual evapotranspiration (aET), river outflow, effluent streams (losing streams) etc. A mass balance approach assumes that all the major elements in the systems are known, that these major elements are measurable or can be estimated and that average values determined for these elements are representative of the area considered over the time scale considered (acknowledging there are heterogeneities in complex systems).

6.5 Methods

For the purpose of the water balance the study area was initially divided into two regions (essentially the Waipara and Kowai zones) and then subdivided again to give a total of four sub-regions, shown in Figure 6.4. The initial two regions were defined by surface water catchment areas (which are also groundwater divides of these zones) as it is considered that rainfall falling in this area contributes to recharge to the basins. Furthermore it is assumed that there is no groundwater inflow from outside the boundaries defined in Figure 6.4. The subdivisions into four zones are based on the findings from the hydrogeological, chemical and isotopic analysis (chapters three, four and five).

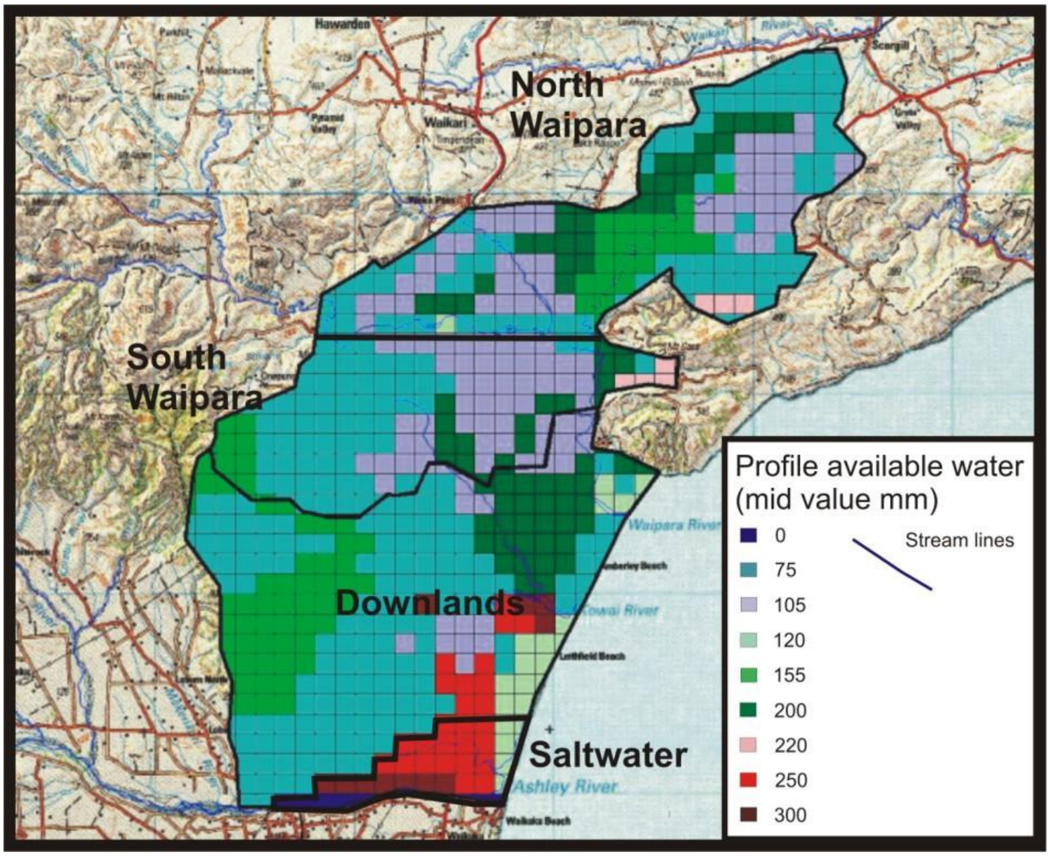

Figure 6.4 Map showing the distribution of mid total profile available water (PAW) values for soils in the study area. Mid PAW values are based on values from land resources information system spatial data GIS layer (Newsome at al, 2000) manually interpolated onto a kilometre spaced grid. Also shown are the approximate boundaries of the sub-regions in the water balance.

Rainfall and aET have been calculated using the Scott (2004) model. This model produces monthly values of rainfall and aET for a specified area from NIWA's virtual climate station grid. The grid is spaced at 0.05º latitude – longitude, covering the entire study area and provides daily estimates of the pertinent climate data.

To set up the Scott (2004) model a kilometre spaced grid square was superimposed over a land resources information system spatial data GIS layer (LRISLAY). The

LRISLAY layer contains an estimate of the mid total profile available water (mm) for a soil profile to a depth of 0.9m or to the potential rooting depth if less (Newsome et al, 2000). The mid PAW values were then manually interpolated to the kilometre spaced grid square (Figure 6.4). The output from this exercise was a list for each sub-region containing X and Y coordinate for the centroid of each square, a mid PAW value, an NIWA climate station identifier and an area in square meters. These data were fed into the Scott (2004) model to produce estimates of rainfall and aET. The monthly values of these parameters were manipulated to produce geometric means based on data from 1972 – 2008 and converted into cubic metres of rainfall per year per sub-region.

Mean flows for rivers/streams have been taken from reports, or estimated from gauging data or recorder data. Ashley River total losses have been estimated (Bowden et al, 1982 and Chater, 2004) but this represents losses to both sides of the river. To estimate the proportion of the loss recharging the Kowai zone, three estimates were used in the balance (125 L/s, 250L/s and 375L/s). The estimate for abstraction data is based on the assumption that 60% of estimated consented volume is used. The inflow value to the Saltwater Creek sub-region is calculated as 25% as the total net recharge to the Downlands sub-region, based on the proportion of the area jointly shared in map view.

6.6 Results and discussion

6.6.1 North Waipara sub-region

From the results in Table 6.1 it can be seen that the North Waipara sub-region is recharged primarily by rainfall. This rainfall estimate however includes rain falling on Tertiary and Quaternary sediments. It is interpreted that the potential Tertiary aquifers is being recharged by rainfall and it is interpreted that these potential aquifers have minimal hydrological interaction with the Quaternary formational aquifers (section 6.3.1). As such, a proportion of the rainfall should be assigned to the Tertiary sediments. Approximately 50 - 60% of the area included in the rainfall calculation is underlain by Tertiary sediments. Unfortunately little is known about the infiltration capacity of these sediments. As such no attempt has been made to differentiate the rainfall quantity on the basis of what sediments they land on.

Significant losses from the major creeks and streams in the North Waipara sub-region were discussed by Lloyd (2002). An estimate of the outflow from the Omihi Stream was made based on the median of all gauging data at Glenray Bridge site (section 3.2.6), which provided a value of $3.7m^3 \times 10^6$ per year. This value is close to the sum of the losses from the Weka, Home and Omihi Streams calculated by Lloyd (2002). Scarf (2007) calculated $8.7m^3 \times 10^6$ per year, though he recognised there was a lack of reliable low flow data for this stream up gradient of the confluence with the Waipara River. This does however indicate that the losses and gains from streams in this sub-region are equivalent in magnitude.

Outflow of groundwater from the North Waipara sub-region has not been calculated. Chemical data (chapter four) and piezometric data (Loris, 2000) suggests that regional groundwater flows Southward, out of this sub-region and into the South Waipara sub-region. Groundwater outflow is difficult to measure. One technique is to assume no net change in storage and then reconfigure the balance equation to make groundwater outflow the product. However water level data shown in section 3.5.2 clearly show this assumption is unjustified for shallow wells in the lower Omihi valley (N34/0058). As such no attempt has been made to estimate this element.

6.6.2 South Waipara sub-region

The South Waipara sub-region is primarily recharged from rainfall. Like the North Waipara sub-region it is likely that a proportion of the rainfall should be allotted to the Tertiary sediments, though in this sub-region there is less exposed outcrop (approximately 35% of the total area). Gauging data on the Kowai River (NB) shows that there is likely to be a small quantity of river recharge delivered to the Southwest corner of this sub-region, but a slightly larger volume discharging from the Amberley Swamp. Furthermore this is a minimum estimate as flow from Eastern Creek has little available flow data.

Table 6.1 Water balances for sub-regions of the Waipara – Kowai zones (shown in Figure 6.4). Explanations for the values are provided in the text. A, B & C are estimates of the percentage of flow from the Ashley River to the Saltwater Creek sub-region.

	North Waipara	South Waipara	Downlands	Saltwater	A (5%)	B (10%)	C (20%)	Comments
Area (ha)	**16645**	**13167**	**25410**	**3090**				
Units	**$m^3 \times 10^6$ per year**	**$m^3 \times 10^6$ per year**	**$m^3 \times 10^6$ per year**	**$m^3 \times 10^6$ per year**	**$m^3 \times 10^6$ per year**	**$m^3 \times 10^6$ per year**	**$m^3 \times 10^6$ per year**	
				Inputs				
Rainfall	117.1	96.3	189.1	21.3				
				Surface water losses				
Ashley					3.9	7.9	15.8	Estimated total loss from the Ashley River of 2500L/s Bowden et al (1982) and Chater (2004).
Kowai (SB)			1.7					Median of all gauging data. Site: Mount Grey
Waipara (below Teviotdale)			5.6					Chater (2003)
Intermittent streams	n/a	n/a	?	0.0				May be significant in the Kowai zone
Kowai (NB)		0.8						Taken from section 3.2.4.
Waipara (above Teviotdale recorder)	0.0							Loris (2000) and Lloyd (2002)
Weka Creek	1.7							Lloyd (2002), Aqualinc (2005)
Omihi Stream	0.9							Lloyd (2002), Aqualinc (2005)
Home Creek	1.3							Lloyd (2002), Aqualinc (2005)
				Flow inwards				
Waipara (White gorge)	43.8	43.8						Scarf (2007)
GW inflow	0.0	0.0	0.0	16.3[1]				[1]Estimated at 25% of known net recharge to the Downlands.
Total	**164.9**	**140.9**	**196.4**		**41.5**	**45.5**	**53.4**	

Outputs								
aET	83.2	66.4	131.1	19.1				Geometric mean of 1972 - 2008 NIWA virtual climate stations
Surface water gains								
Coastal Stream (Spring flow)			?					May be significant in the Kowai zone
Saltwater Creek (Spring flow)				15.7				Median of all gauging data. Site: Factory Road Bridge. Including 60% of SW consented takes (volumes calculated from maximum consented rate).
Boyne Creek				2.7				Based on one gauging only. Site: Confluence Boyne and Bairds Creeks. Including 60% of SW consented takes (volumes calculated from maximum consented rate).
Kowai (NB)		1.2						Median flow (2006 - 2009). Site: Recorder at Grays Road.
Doc Creek		?						
Flow outwards								
Waipara (mouth)			25.4					Median of all gauging data
Kowai (SH1)			0.0					Median of all gauging data
Waipara (Teviotdale)	66.0	58.6						Scarf (2007). It is assumed that this value includes contributions to Omihi Stream. Output from the Omihi Stream has been added to the North Waipara sub-region value and deducted from the South Waipara sub-region.
GW outflow	?	?	16.3[1]	A - B[2]				[1]Estimated at 25% of known net recharge to the Downlands. [2]Assumed outflow is equivalent to the difference in input/ output estimate A or B
Abstraction	1.8	3.5	1.7	1.7				Assuming consents abstract 60% of take (excluding non-consumptive takes).
Total	**151.0**	**129.7**	**174.6**		**39.3**	**39.3**	**39.3**	
Inputs - Outputs	**13.9**	**11.2**	**21.8**		**2.3**	**6.2**	**14.1**	
Inputs – Outputs (%)	**8**	**8**	**11**		**5**	**14**	**26**	

Outflow from this sub-region has not estimated. Water level data (section 3.5.2, M34/0311) shows that there is a net loss of storage in some of the shallow wells since monitoring of this well commenced in 1999.Chater (2003) suggested that 177L/s was lost from the Waipara River to groundwater below the Teviotdale recorder to the next gauging site (Greenwoods Bridge). The majority of the area between the two gauging sites is underlain by Tertiary sediments. Concurrent gaugings show that there is typically a loss from the river flows between Greenwood Bridge and the mouth. There is a discrepancy between the mean flows at Teviotdale recorder, Chater (2003) calculated loss and flows at the mouth. This is due to the use of data from numerous sources, produced for different purposes, using different methods.

6.6.3 Downlands sub-region

The Downlands sub-region receives significant recharge from rainfall. There is however 9000 – 10000ha of land covered by varying thicknesses of loess in this sub-region. It is likely that these cover deposits impede drainage with the result that a proportion of this rainfall will be diverted to channels via interflow, runoff and stream flow. On the S4 and younger surfaces where the channels are likely to be gravel lined significant recharge may occur (intermittent stream recharge). These streams have not been gauged so no attempt has been made to estimate their flow.

Springs occur along the coast at the base of the marine cut terrace in this sub-region (Section 3.2.7). The discharge from these springs has not been measured so no attempt to estimate this output has been made. Total groundwater outflow from this sub-region has not been attempted because of uncertainties in inputs and outputs.

6.6.4 Saltwater Creek sub-region

The major recharge source to the Saltwater Creek sub-region is Ashley River recharge and inflow from the Downlands. Direct rainfall infiltration is limited in this region due to the high PAW values retaining a significant amount of moisture (90% of rainfall in this sub-region is consumed by aET). Three estimates of Ashley Recharge have been used in the balance. The best fit value for this sub-region is 125 – 250 L/s from the Ashley River, which leaves 2250 - 2375 L/s recharging the Ashley zone to the South. These values however are reliant on the estimate of groundwater inflow from the Downlands sub-region and output estimates. The net recharge to the Downlands sub-region has been used because of uncertainties caused by being unable to estimate the inputs from the intermittent streams. As such it may in fact represent a maximum value.

Discharge from this sub-region is from spring fed streams. A proportion (60%) of surface water abstraction data has been lumped onto the median gauging values to estimate these flows. The gauging sites used are located up gradient of SH1 so they likely represent most of the discharge coming from the springs, but are not affected by seawater moving up the channel at high tide. It should be noted that the estimate for Boyne Creek is based on one gauging. Outflow from this sub-region is assumed to be the difference between inputs and outputs. Water level data indicates that there were no significant changes in storage. It is likely that a proportion of this difference is spring fed surface water flow which has not been accounted for (between SH1 and the coast).

6.6.5 Discussion

It was noted during the analysis that in the Kowai zone a considerable amount of the abstraction occurs in the saltwater sub-region. This is because groundwater and surface water resources are readily available and reliable. In the Downlands sub-region successful wells are rarer. In addition, land use has evolved from pastoral farming to lifestyle blocks and cottage industry pursuits (section 1.7.2). However the constant inputs to this sub-region from the Ashley River and its total area suggest that sub-region it is likely to be quite resistant. Furthermore a significant proportion of this region is already irrigated (>50%). Given this and the difficulties of finding reliable groundwater on the upper downlands suggests that the Kowai zone may never be fully allocated.

Water level observations (section 3.5.2) clearly show declining water levels in shallow wells in the Waipara Basin. This negative change in storage was not revealed in the water balance analysis. This is due to the inability to assign values to the elements, for example rainfall recharge to the potential Tertiary aquifers. Alternatively this may indicate that long term averages need to be used with caution in this setting. Virtual climate data for the North Waipara sub-region reveals that the total rainfall for three of the last four years has been less than the long term average. Bearing in mind that the 2008 rainfall total was only higher than average due to three large separate rainfall events (section 3.2.1), it is likely that irrigation demands during these drier periods are likely to be higher, with greater volumes being extracted now that ever before (section 1.8). This suggests that the decline in water levels is due to the combined effect of abstraction and climate.

Some elements in the water balance have not been estimated due to a lack of reliable data. Furthermore some of the elements that have been estimated are based on crude assumptions. As such it is considered that this water balance has minimum errors in the order of 5 – 14%.

6.7 Chapter summary

Rainfall falling onto the margins and within the basin is the largest source of recharge to the study area. Rainfall falling on the margins is delivered into the basin by interflow/runoff flow down slope onto marginal alluvial fan systems/ fluvial deposits where a proportion of the water infiltrates into the subsurface.

A conceptual model of the downlands has been proposed to indicate the interrelated influences of tectonics, loess deposition and fluvial systems on recharge.

A simple water balance has been conducted (with minimum likely errors of 5 – 14%) for the study area. A number of the water balance elements have not been estimated, particularly groundwater outflow because water level data for shallow wells show that it is unjustified to assume no net change in storage for the Waipara Basin. However rainfall is thought to be the predominant source of recharge to the study area except for the Saltwater Creek sub-region, where Ashley River recharge and groundwater flow from Downlands dominate. These recharge interpretations are consistent with chemical, isotopic and field observations.

7 Chapter seven: Summary and conclusions

7.1 Introduction

The primary objective of this thesis is to qualify and quantify recharge to the study area. The aim was to build on previous work (Loris, 2000. Lloyd, 2002) in determining groundwater recharge sources. In addition it was intended to produce a geomorphic map on which to base an interpretative history, to identify previously unrecognised tectonic structures and to describe them, to provide hydrogeological conceptual models of recharge to the area, and to assess the appropriateness of the current boundary between the Kowai and Waipara zone.

7.2 Background

7.2.1 Land use

Land use in the Waipara – Kowai zones has been estimated by producing a simple map. A single land use was assigned to a property or land parcel, therefore some land uses may have been overestimated (see section 1.3.1).

This map was compared to an earlier land use map (Lloyd, 2002) to estimate the rate of change of horticultural and irrigated pasture on the Waipara Basin floor. In 1976 horticulture occupied 0% of the total area; in 2009 it was 10%. Irrigated pasture in 1976 cover 0.1% of the total area and in 2009 it covered 14%. This mapping indicates that the use of land in the Waipara basin has significantly changed from dry land farming towards irrigated land uses. Similar conclusions were made by Loris (2000) and Lloyd (2002).

No existing land use maps of the Kowai zone were located. The agricultural history of this zone has been described by Fox et al. (1964) and Bowden et al. (1984). Using this information, anecdotal evidence and field observations indications are that the recent land use trend (10 – 15 years) in the Kowai zone is towards small life style blocks or cottage industry type activities.

7.2.2 Groundwater use and development

The demand for groundwater was qualified by plotting the total numbers of wells drilled in the study area through time. This showed that before 1990 there were very few wells being drilled, but between 1991 and the present over 300 wells have been drilled. This figure is 5.5 times greater that the total number of wells drilled between 1900 and 1990. This suggests that since 1990 there has been an increase in demand for groundwater within the study area.

An attempt to quantify the demand for groundwater was made, by totalling the estimated consented volumes by zone. This showed that the estimated consented volumes of groundwater in the Waipara zone had increased by a third since 2004. In the Kowai zone the demand for groundwater had decreased during the same period. An estimate of the usage was calculated by assuming all consents use 60% of their consented volume. This assumption is based on the work of Sanders (2000).

From the previous sections it is concluded that the water use in the Waipara basin has increased significantly since the 1990's, due appreciably to changes in land use. In the Kowai zone there has been a decrease in demand for groundwater in recent times.

7.3 Geomorphology and active tectonics

7.3.1 Geological setting

The study area is located in Pettinga et al. (2001) domain four and near domain three. Domain four is defined by thrust faulting and related folds caused by compression as a result of oblique shortening. Domain three is the PPAFZ and consists of strike-slip, transform and reverse faults. The PPAFZ is likely to represent the juvenile member of the MFZ that transfers strain from the Alpine Fault to the to the Hikurangi margin. Deformation of the area has shaped the basin and its contents.

7.3.2 Geomorphic mapping

A geomorphic map of a part of the study area was constructed. Nine geomorphic surfaces (Bull, 1991) were defined based on soil data (provided by T Webb, Landcare Research Ltd), aerial imagery and field work. Each surface was inferred a distinct age, except S6 which is poorly defined (>73 ka). Field observations and bore log data from Environment Canterbury's wells database was used to gain an understanding of the geology beneath the geomorphic surfaces. Geomorphic interpretations of the remaining area on the Waipara basin floor were based on Harris (1982), Nicol et al. (1994) and Finnemore (2004).

7.3.3 Seismic reflection surveys

Three hammer and plate source seismic reflection surveys were conducted in the Waipara basin. Line 1 and 2 were intended to image the Broomfield Fault in the Southern Waipara basin. Line 1 did not image the fault, but showed some recent deformation. The gross structure of the Quaternary sediments was imaged and it was found to be a thick sequence of recent material overlying Canterbury, Teviotdale and Kowai Formations. Line 2 clearly showed the Broomfield Fault. It is interpreted that on the up thrown side of the fault, Kowai formation has been raised to the surface. Line 3 aimed to find an inferred fault shown on Loris (2000) geological map. The fault was not imaged. However it is interpreted that the profile shows the buried extension of the Onepunga Anticline.

7.3.4 Morphometric analysis

Hack's (1973) stream gradient index method was used on selected streams in the study area to distinguish recent deformation. The analysis gave better definition to the length of two known faults in the study area. The analysis when viewed with the stream profile showed that the Kowai zone is stepped. The steps coincided with geomorphic surfaces indicating they formed during distinct time periods.

Drainage patterns in the upper catchment of the Kowai River (NB) were examined. The drainage patterns indicate tilting, in that the channels of the major stream are all incising into the Northern bank with terraces preserved on the Southern bank. Additionally, air gaps cutting into Mount Brown Formation were identified in this area. These air gaps are at an elevation of >300masl and are interpreted to indicate that Waipara River previously flowed through this valley sometime before 73 ka.

7.3.5 Landscape evolution

The results of the preceding investigations were used to determine an interpretive geomorphic history of the study area.

The Kowai zone is dominated by the Kowai Anticline in the West (Hoolihan, 1978) and the Pacific Ocean in the East. It is interpreted that the Kowai zone has formed due to the interaction of eustatic sea-level, climate and tectonics. During glacial periods global sea level drops allowing rivers to aggrade to lower base levels. In the interglacial periods global sea level rises as ice caps melt. In the Eastern part of the Kowai zone this is represented by alternating sequences of marginal and marine sediments interfingering with terrestrial deposits. During the Holocene, the sea level reached a high stand which incised into the terrestrial deposits forming a cliff. In the late Holocene the coast has prograded outwards (Shulmister and Kirk, 1993). In the West as the Kowai Anticline is uplifted and eroded the Kowai Formation and tertiary sediments are being exposed in the core of the Anticline (Cowan, 1992). As the area is being uplifted, fluvial and alluvial sediments (often overlaid by loess) are being preserved.

In the Waipara basin deformation during the Quaternary has uplifted the coastal hills (Yousif, 1987. Nicol et al. 1994). Preserved in the centre of the basin are two formations that are likely to date from the late Pleistocene. Around the margins of the basin alluvial fans are transferring sediments eroded from the uplifting margins to the basin floor. The alluvial fan sediments on the Waipara Downs are interpreted to be interfingering deposits with Waipara River fluvial deposits. The Omihi valley has formed in response to uplift on the Omihi Fault which confined the stream to the Western margin. Additionally this uplift created exposed material which was eroded, and transposed down the slope into the largest alluvial fans. The Kowai River (NB) flows along the margin of the Waipara fan.

7.4 Hydrology and Hydrogeology

7.4.1 Hydrology

During the study period three significant rainfall events occurred; February, July and August 2008. These events accounted for 50% of the total annual rainfall at NIWA's station at Amberley.

Visual gauging was undertaken on a number of streams in the Kowai zone to gain an understanding of the hydrology. The results show that streams flowing onto the downlands tend to be influent and ephemeral. In the Saltwater Creek area there is continuous flow. Instantaneous gauging on the Kowai River generally showed that during low flows the River gains flow in the upper catchment and that the flow is lost to groundwater downstream. In more detail the Kowai River (NB) gains flow from the

Amberley Swamp (which is impounded behind the Broomfield Fault) and springs above Amberley Township. Springs occurrence was described and it was concluded that they could be used to indicate local flow directions.

7.4.2 Hydrogeology

In this study Fetters (2001) definition of an aquifer was used. As such aquifers were defined by geological formations.

Yield and specific yield data from wells in the study area was plotted. This showed that in the Waipara zone yields increased with depth but specific yield decreased with depth. The increasing yield with depth is explained by the fact that deeper wells have greater available drawdown. In the Kowai zone relatively high yielding, high specific yields were noted in the Saltwater Creek area, near rivers and streams. On the downlands the yields and specific yields were low. Limited aquifer tests conducted in the Waipara basin were examined. The average and geometric mean of transmittivity from the Waipara basin are one to two orders of magnitude lower than an "average plains well". Low transmissivities of the Waipara basin aquifers were noted by Loris (2000) and Lloyd (2002). Aquifer tests were also examined to reveal information about pumping interference. On a number of occasions the pumping of deeper wells affected shallower wells, while other tests showed limited response from the observation bores. This indicates that there is potential for pumping interference in the Waipara basin and that the basin fill is complex. Water level data from the study area was explored. Water levels were used to indicate recharge sources and provide a check for chemical and isotopic data.

7.5 Groundwater chemistry

There is a large dataset of chemical data collected from surface water and groundwater sources available. It was decided to make use of this resource. The data was examined using various methods.

The results of the analyses suggested that the study area could be divided into four Hydrochemical zones; North Waipara, South Waipara, Downlands, Saltwater Creek. North Waipara zone has relatively high concentration of most determinants reflecting the input of tertiary sediments from the margins, particularly limestone and salts. The chemistry of the water in the South Waipara zone showed lower concentration of most determinants when compared to the North Waipara zone. The fluvial sediments here are predominately composed of Torlesse super group which are likely to be relatively inert. The chloride and nitrate nitrogen concentrations of sites in this zone suggest rainfall recharge (Haywood, 2002). The Downlands zone has similar concentrations of ions as the North Waipara zone, except (amongst others) it had the highest average concentration of Chloride. The high Chloride concentrations are likely to come from salts within the interbedded marginal marine and marine sediments that occur in this zone. The chemistry data supported by water level data show that this zone is recharged by a mixture of rainfall, the Waipara River and small ephemeral streams. The Saltwater Creek zone has the most distinctive average chemical signature. The TDS, chloride and nitrate nitrogen concentrations suggest recharge from the Ashley River and Southeasterly flowing groundwater emanating from the Downlands zone.

7.6 Stable isotopes and Groundwater dating

7.6.1 Stable isotopes

An extensive stable isotope sampling programme of surface water, groundwater and rainfall was initiated for this project. Due to unforeseen circumstances the data was analysed in December following the completion of the sampling programme. Once the analysis was completed the data was extensively tested. The testing showed that some of the samples had degraded because of exposure to the atmosphere.

Rainfall data collected from sites on the plains was used to estimate the altitudinal effects on the stable isotope compositions, resulting in a lapse rate of -0.43‰ $\delta^{18}O$ per 100m change in elevation. This relationship was used to interpret the data collected in the study area. In the Saltwater Creek area it was found that many wells had similar isotopic compositions to the Ashley River, with sites on the Northern margins reflecting mixing with rainfall. The stable isotopic compositions of wells in the Downlands area reflect inputs from ephemeral streams, rainfall and the Waipara River. In the South Waipara area stable isotopic compositions are more depleted than expected. It is interpreted that this represents mixing of rainfall falling at different elevations. In the North Waipara area stable isotopic compositions reflect inputs from rainfall and stream recharge.

7.6.2 Groundwater dating

Six ^{14}C date were acquired from wells in the study area. Two samples were collected by J Weeber in 2007. The ^{14}C results showed that deeper groundwater in the basin is several thousand years old. The oldest dates were collected from wells in the Omihi valley. From the chemical investigations it is clear that this area contains a significant amount of limestone clasts. The input of fossil carbonate is likely to have led to overestimations of the ages. These wells were sampled by Loris (2000) and had background concentrations of tritium indicating old water. It is interpreted that the mean age from these wells are likely to be several thousand years. The spatial distribution of these wells and ages suggest that there is significant impoundment of groundwater, which is interpreted to represent active deformation of emerging tectonic structures within the basin fill.

A spring near the confluence of the Omihi Stream and Waipara River was dated using Tritium, CFC's and SF_6. The ages were somewhat ambiguous but have been are interpreted to represent young (mean age 7 – 11 years) waters.

7.7 Conceptual hydrogeological models and water balance

It is envisioned that the primary driver of the groundwater system in the study area is gravity (Toth, 1963. Freeze and Witherspoon, 1967). In the Waipara basin, based on chemical, isotopic and field observations it is argued that rainfall falling on the margins of the basin is contributing to recharge as well as rainfall falling in the centre of the basin. It is also envisioned that active structures in the Waipara basin are impeding the passage of groundwater flow through the system. It is clear from chemical, isotopes, geophysical and water level data that the Broomfield Fault is a hydrological boundary for shallow groundwater. This indicates that it is a logical boundary for the Waipara and Kowai zone.

The conceptual model for the Kowai zone is that rainfall falling on the Kowai Anticline (Kowai Formation) due to the steep slopes and hydraulic properties of the sediments diverts a proportion of the rainfall as interflow and runoff into the valley systems. Thus streams flow out onto the younger sediments down gradient and as they do they lose water to groundwater. Rainfall on the downlands is limited due to the loess cover.

The water balance attempted to quantify the inputs and outputs to the groundwater system as conceptualised in the preceding sections. A number of the elements were not estimated due to uncertainties or a lack of information. The water balance showed that rainfall is the predominated source of recharge to the study area, with localised but important inputs from stream and rivers.

7.8 Recommendations

7.8.1 Resource monitoring and evaluation

- Currently there are four wells being monitored in the Kowai zone by Environment Canterbury as part of it monthly survey. Three of these wells are shallow (<10m deep) and are located on the downlands. To improve the understanding of the groundwater system a better distribution of wells is needed. It is recommended that eight wells are added to the monthly survey; M34/5813, M34/5689, M34/5611, M34/0178, M34/0165, M34/0620, M34/0192 and M34/0734. Furthermore it is suggested that a deep well located on the downlands be monitored.
- Further spring mapping is required in the Kowai zone; particular in the Saltwater Creek area and along the Holocene marine cut terrace.
- In order to gain a better understanding of the flow regime of the Omihi Stream it is recommended that a temporary automatic flow recorder be installed in the lower reaches before the confluence with the Waipara River.
- The Kowai River (NB), Doc Creek and Eastern Drain previously have not been recognised as an output from the Waipara zone. Here the median flow rate at the Kowai River (NB) recorder was used and no robust flow data is available for Doc Creek. It is suggested that Doc Creek be gauged to provide an output estimate.
- It has been interpreted that rainfall on the margins is recharging the Waipara basin and it is may be an important recharge source to smaller basins. This recharge is not being considered under the current allocation scheme. It is recommended that an investigation into this recharge mechanism be instigated. One suggestion is to install a number of shallow piezometers along a transect perpendicular to topography and to monitor the water levels. If a storage value

can be determined or estimated the change in water level can be used to estimate recharge (Delin et al. 2006).

- It is likely that part of the rainfall falling on the margins is recharging the potential tertiary aquifers. An estimate of the proportion of rainfall recharging these aquifers is required to complete a thorough water balance.

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